Evidence for modulation at the solar rotation period of the convection electric field, plasmaspheric density, ULF wave power, and energetic particles over the Van Allen Probes Mission

Scott Thaller, J.R. Wygant, C.A. Cattell, A.W. Breneman, E. Tyler, S. Tian, S. De Pascuale, C.A. Kletzing, W.S. Kurth, H. E. Spence, G. Reeves, D.N. Baker, J. B. Blake, J. Fennell, S. Claudepierre

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Cascais, Portugal

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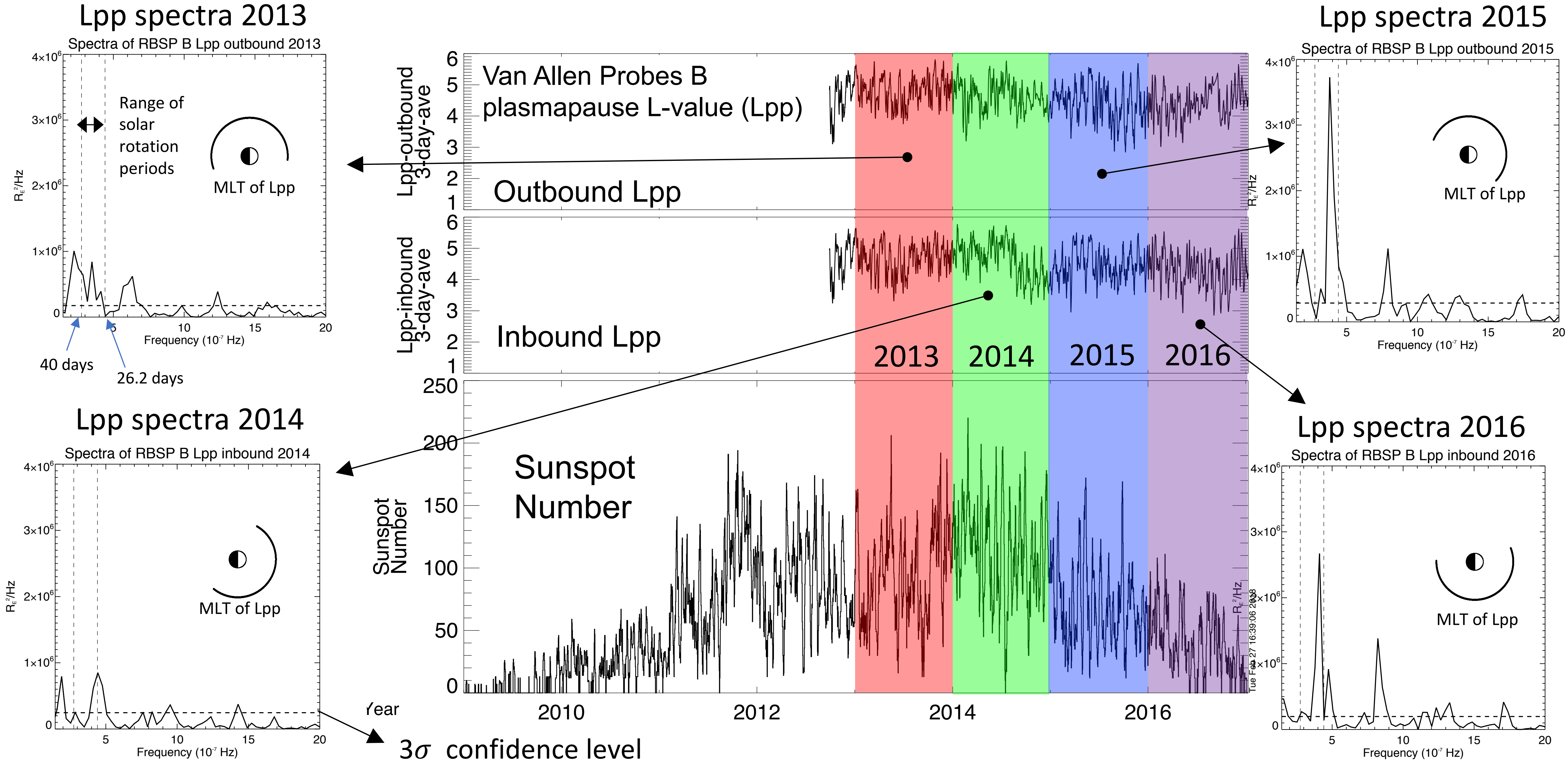
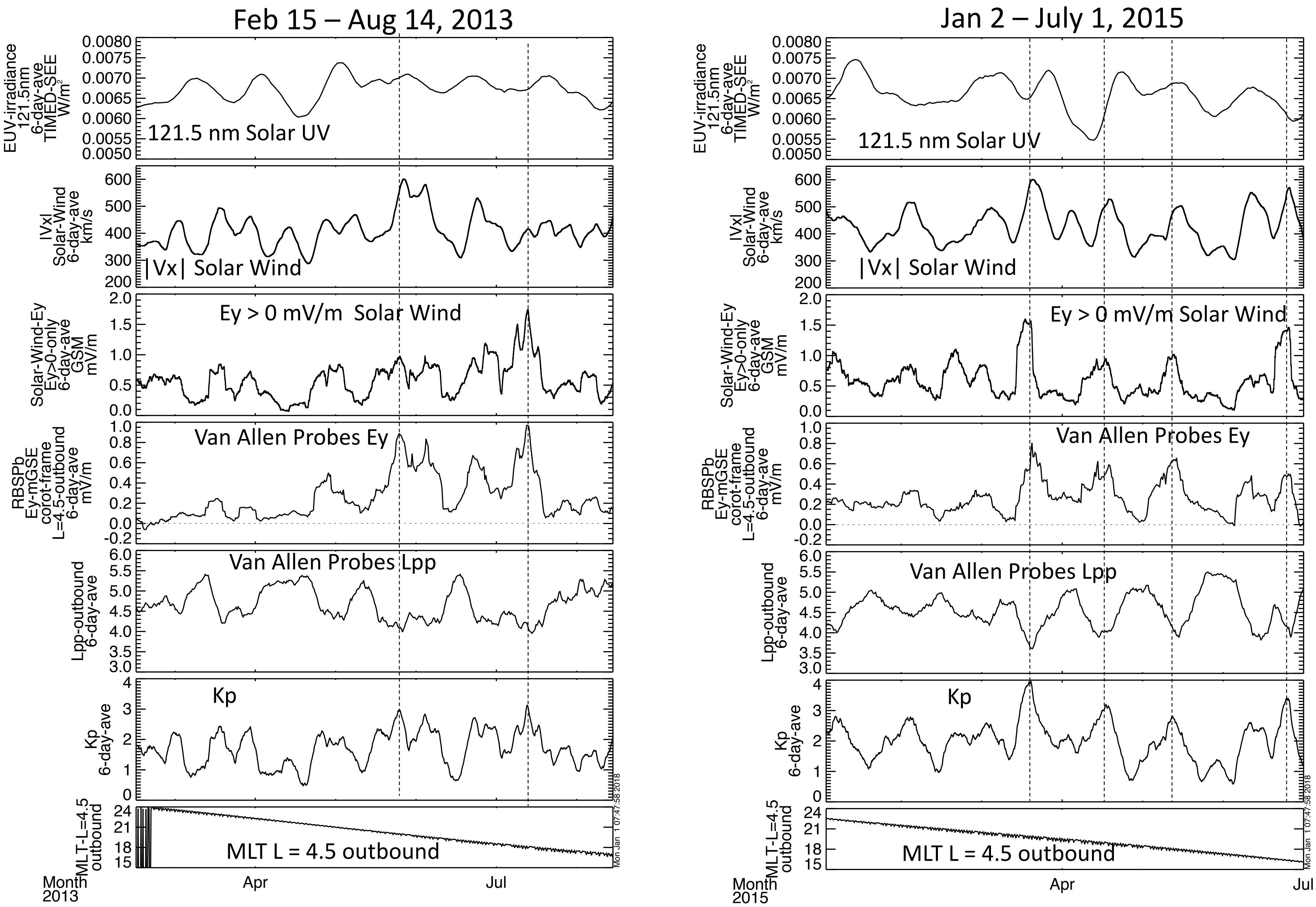
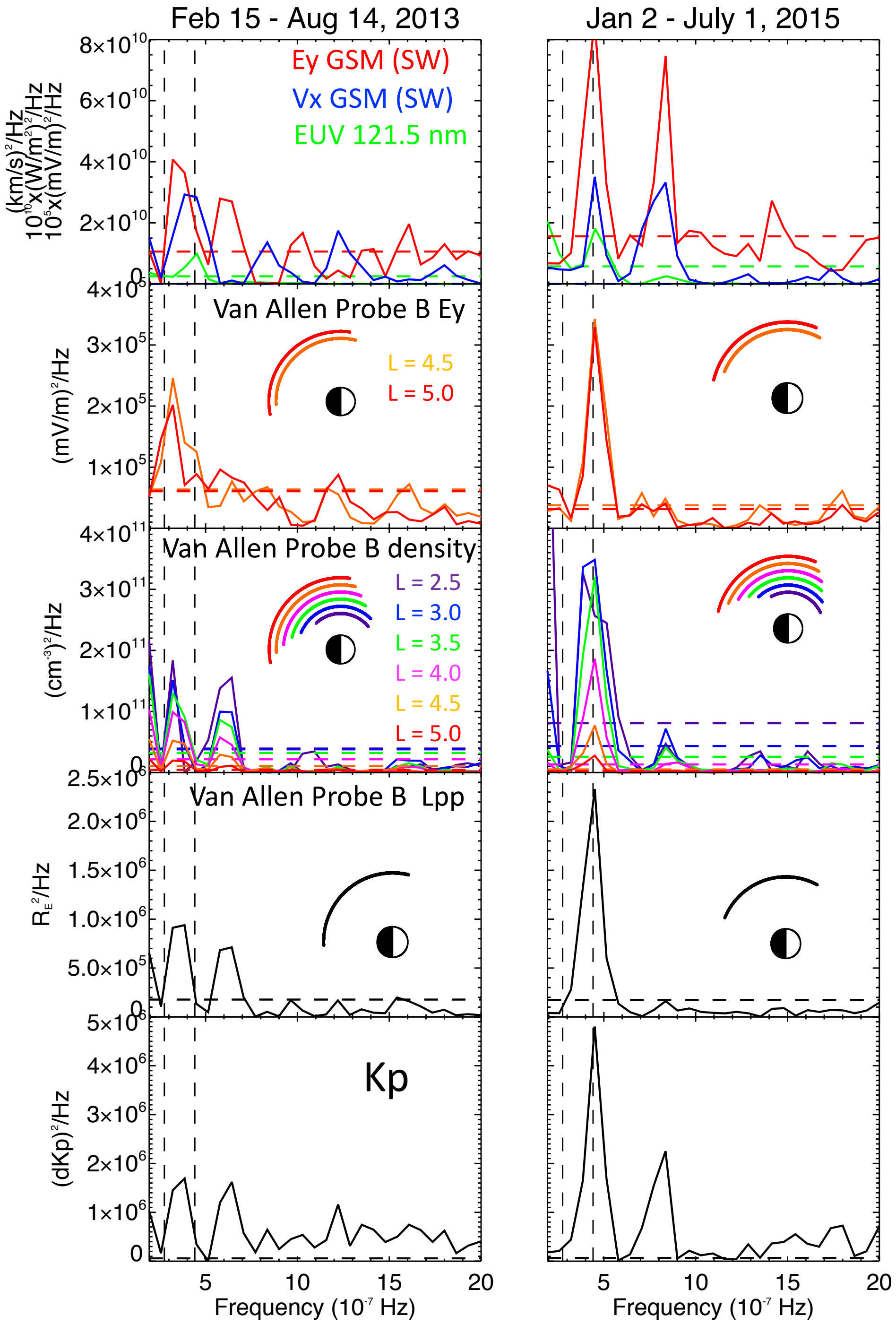
Main Points

- The plasmapause moves in and out at solar rotation periodicities (~27-days).
- By a significant amount: ~ 0.7 R_E on average.
- Driven by convection associated with CIRs.
- Most pronounced in the declining phase of the solar cycle.
- Significant efficiency of the solar wind in driving the convection electric field, ~ 70% at the solar rotation periodicity.
- The outer belt is also strongly modulate at ~27-days, especially at 4.5 L (average Lpp) in the solar cycle declining phase.
- ULF power also shows ~27-day variations; preliminary observations show anti-correlation in the L-value of max ULF amplitude with Lpp.

Change in the modulation of the plasmapause L-value (Lpp) with phase of the solar cycle




Feb 15 – Aug 14, 2013
Jan 2 – July 1, 2015
EUV-irradiance 121.5nm 6-day-ave TIMED-SEE W/m²
121.5 nm Solar UV
|Vx| Solar-Wind 6-day-ave km/s
|Vx| Solar Wind
Solar-Wind-Ey Ey>0-only 6-day-ave GSM mV/m
Ey > 0 mV/m Solar Wind
RBSPb Ey-mGSE corot-frame L=4.5-outbound 6-day-ave mV/m
Van Allen Probes Ey
Lpp-outbound 6-day-ave
Van Allen Probes Lpp
Kp 6-day-ave
Kp
MLT-L=4.5 outbound
MLT L = 4.5 outbound
Month 2013
Month 2015
Apr
Jul



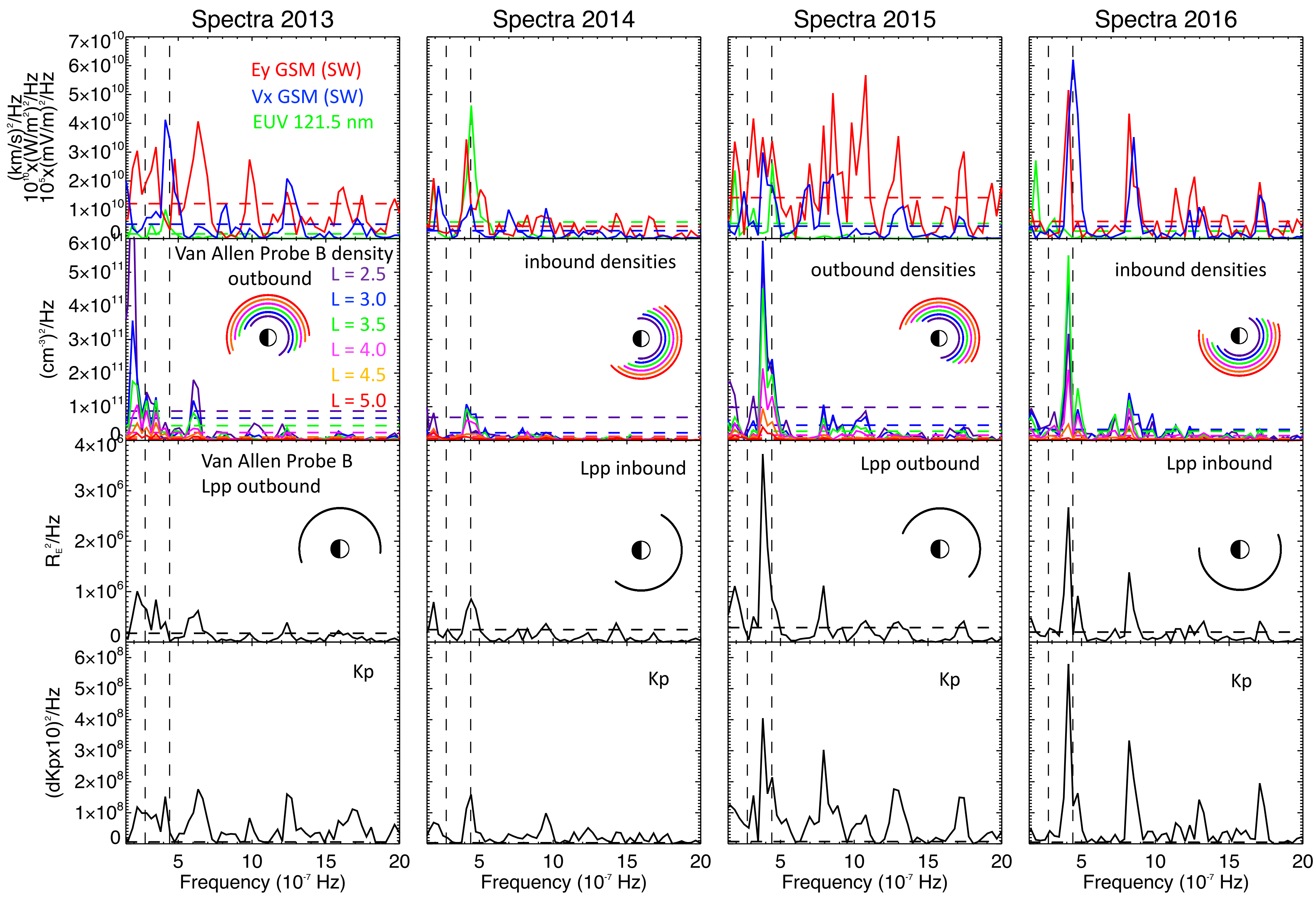
Comparing the spectra of two 6 month intervals, near solar maximum (2013) and in the declining phase (2015). **Magnetosphere quantities from the duskside**.

The **RBSP B dawn-dusk electric field**, Lpp, cold density and Kp show increased amplitudes at frequencies of solar rotation (~27 days) in 2015 v. 2013.

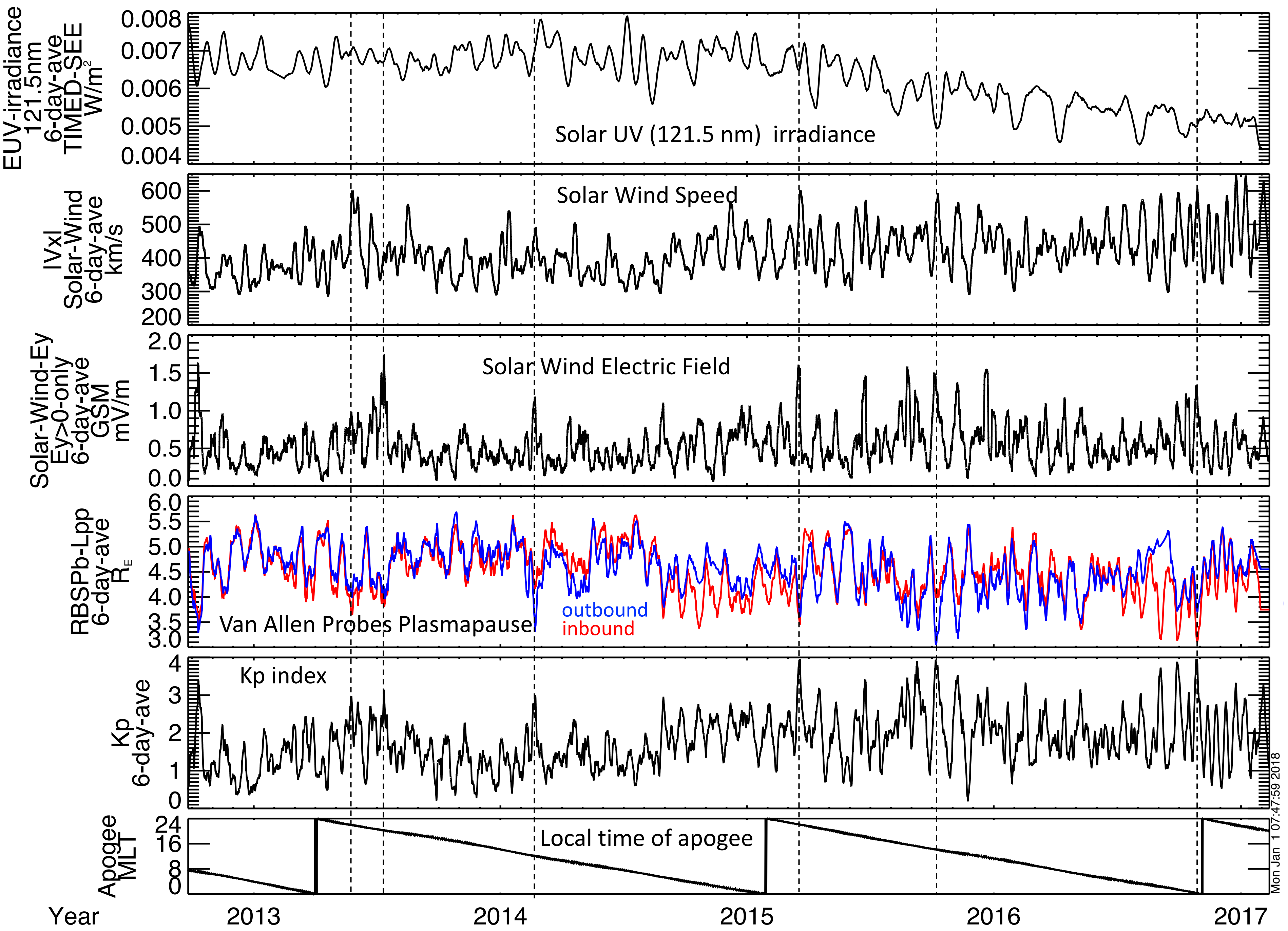
"efficiency of reconnection" (the efficiency of the solar wind in driving the convection electric field) ratio of the peak solar wind electric field to the peak in the local measured electric field.

On timescales of solar rotation periodicities is ~ 70% (determined from the as compared to values determined from the cross polar cap potential of ~15 to 20 % .

Note large peak in 2015 SW Ey does not show up clearly in Lpp, etc. This is a topic under investigation.



Spectra 2013
Spectra 2014
Spectra 2015
Spectra 2016
Ey GSM (SW)
Vx GSM (SW)
EUV 121.5 nm
(km/s)²/Hz
10¹⁰x(W/m²)²/Hz
10⁵x(mV/m)²/Hz
Van Allen Probe B density
outbound
L = 2.5
L = 3.0
L = 3.5
L = 4.0
L = 4.5
L = 5.0
inbound densities
outbound densities
inbound densities
(cm⁻³)²/Hz
Van Allen Probe B
Lpp outbound
Lpp inbound
Lpp outbound
Lpp inbound
R_E²/Hz
Kp
Kp
Kp
Kp
(dKpx10)²/Hz
Frequency (10⁻⁷ Hz)
Frequency (10⁻⁷ Hz)
Frequency (10⁻⁷ Hz)
Frequency (10⁻⁷ Hz)

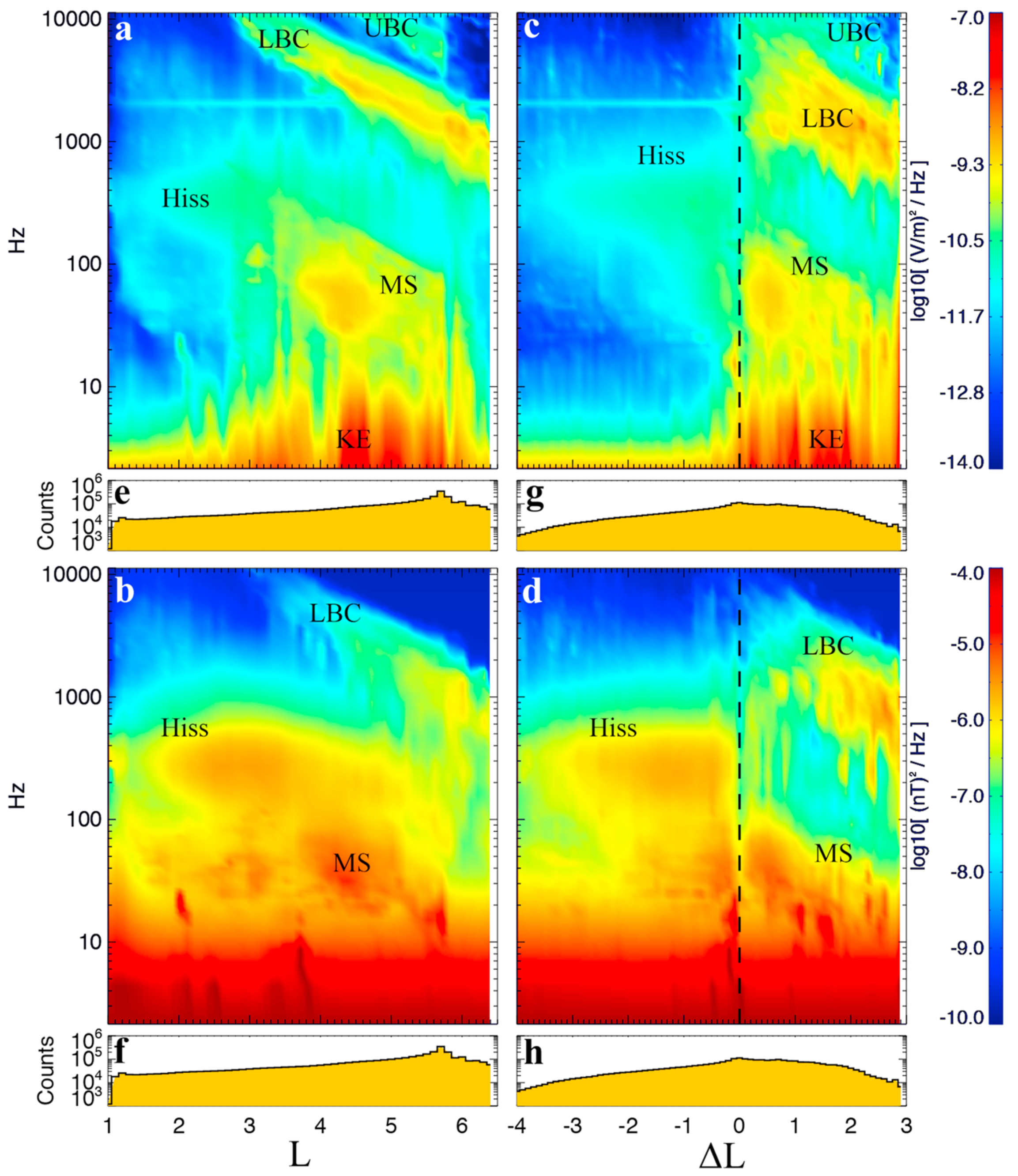


Vertical dashed lines are placed at local peaks in the solar wind electric field.

Note the anti-correlation between the plasmapause location and the solar wind electric field enhancements.

Adapted from Malaspina et al. [2016]

Wave power location is organized by the plasmapause location.

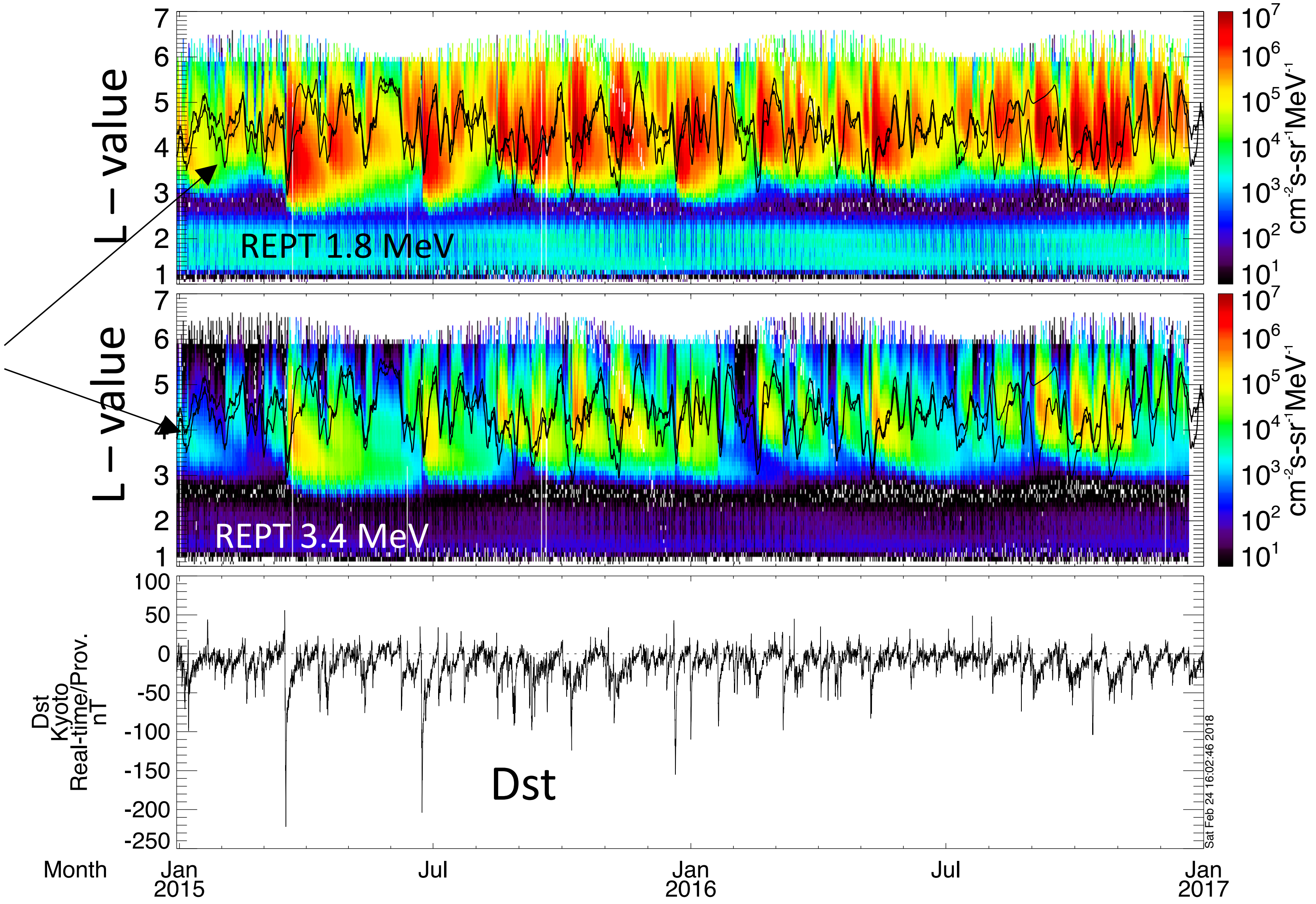


As the plasmapause moves in and out the hiss and lower bound chorus will vary in location, and so to the locations of the scattering and acceleration of MeV electrons.

Van Allen Probes B REPT 1.8, 3.4 MeV electrons 2015 - 2017

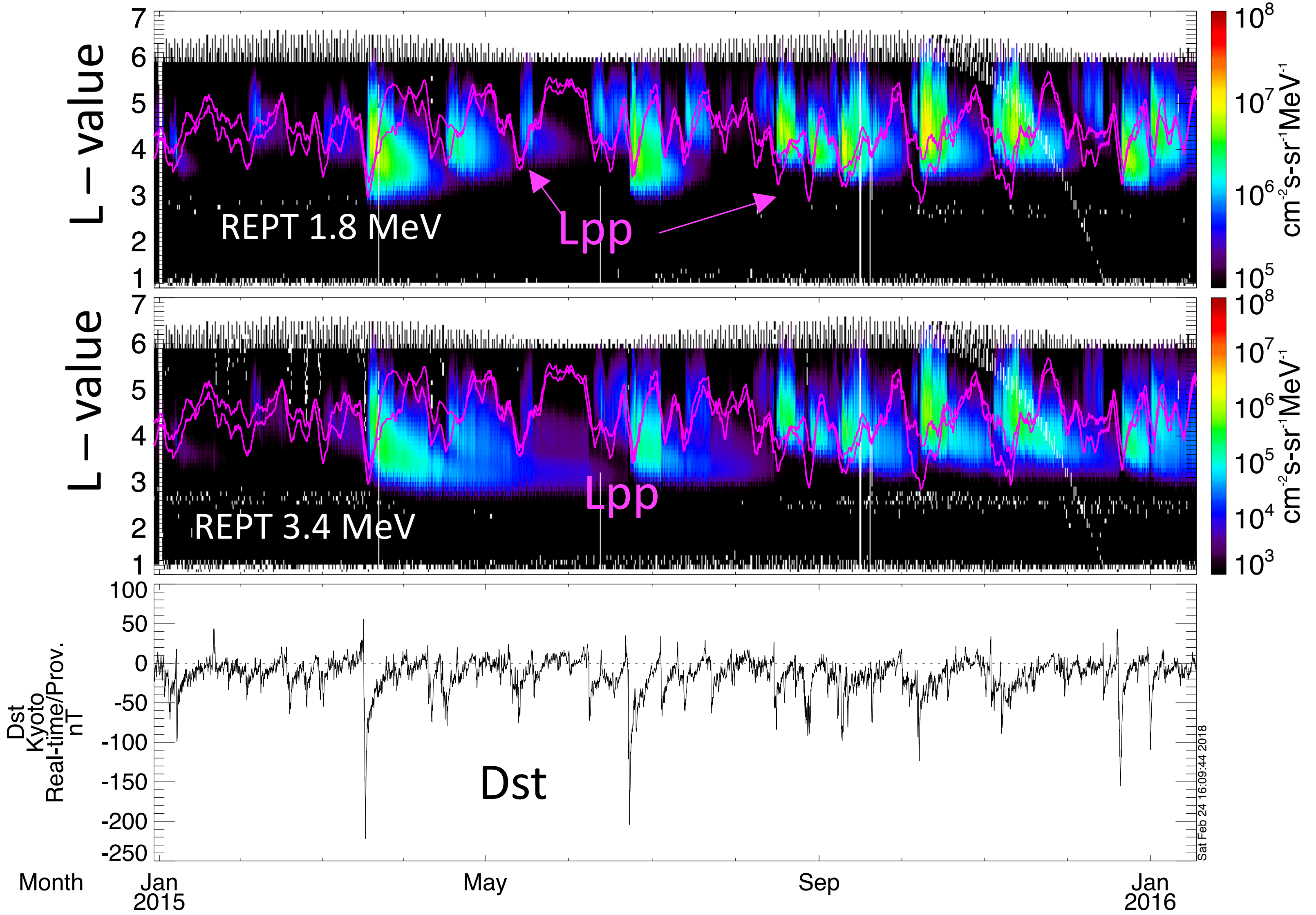
In and Outbound plasmapause L-values, 3-day average.

Note that the plasmasphere is often overlaying a significant fraction of the outer belt

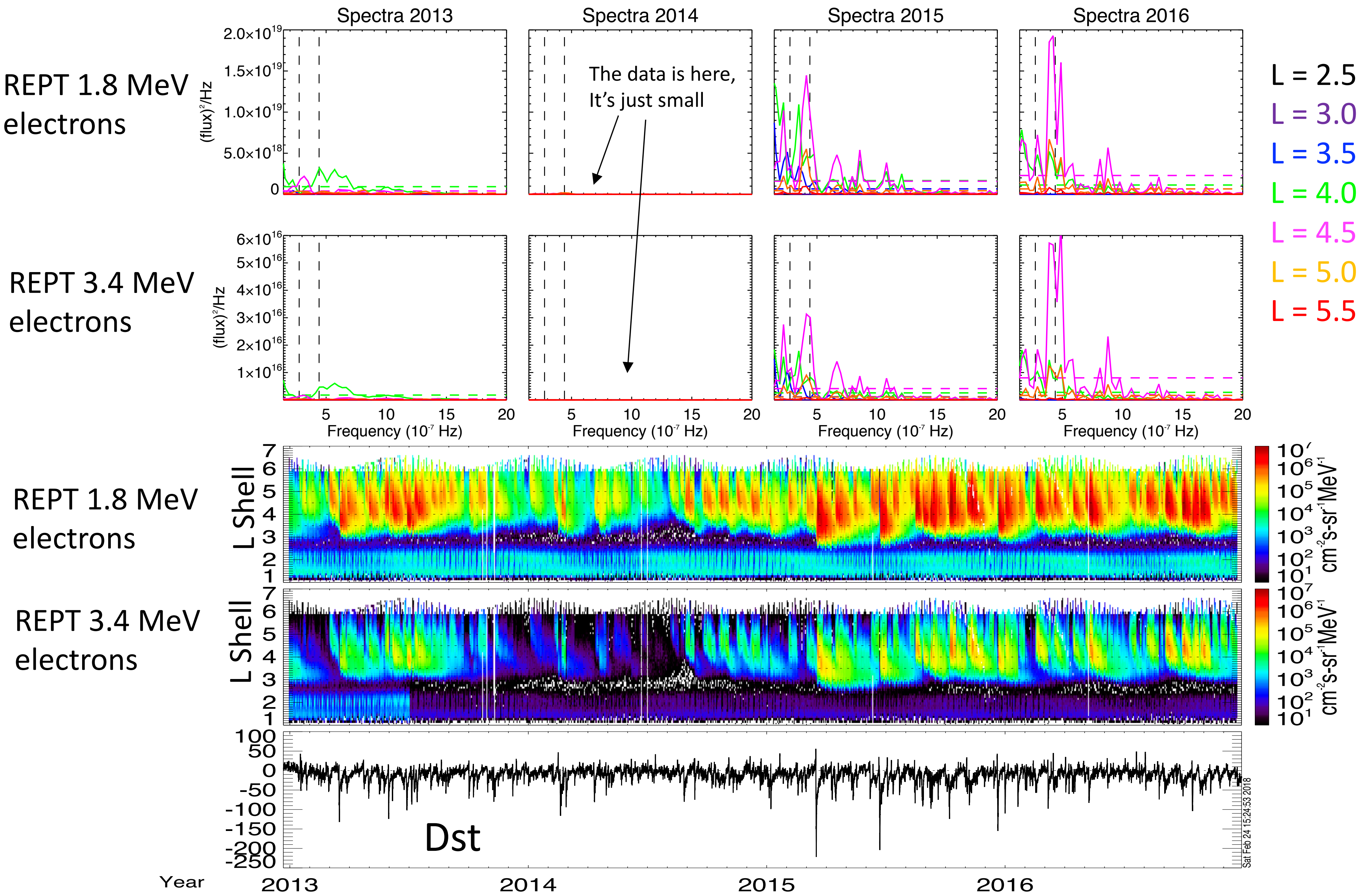


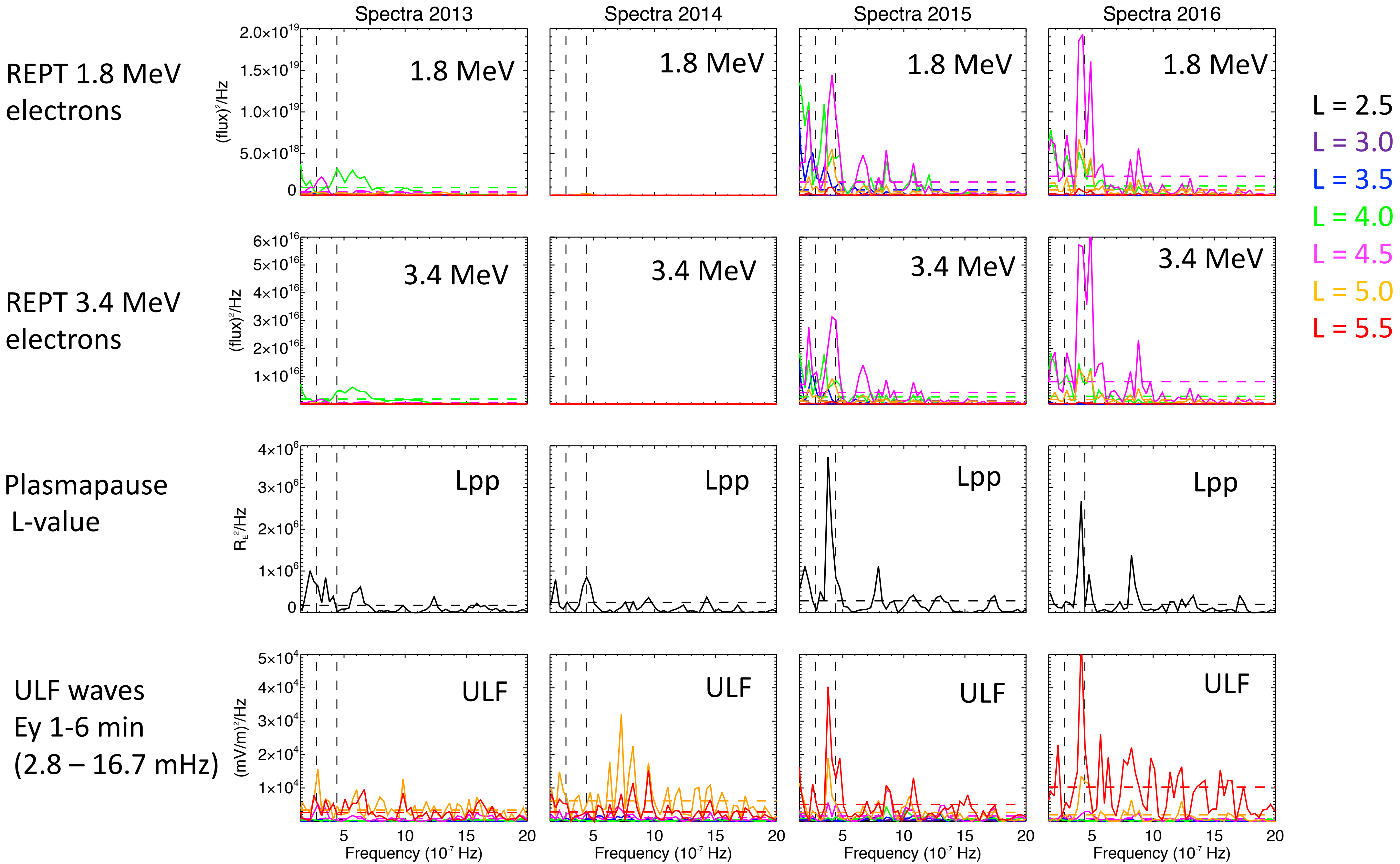
Van Allen Probes B REPT 1.8, 3.4 MeV electrons 2015

Note that the plasmasphere is often overlaying a significant fraction of the outer belt



Van Allen Probes B REPT electrons (outbound)





Spectra 2013
Spectra 2014
Spectra 2015
Spectra 2016
REPT 1.8 MeV electrons
REPT 3.4 MeV electrons
Plasmapause L-value
ULF waves Ey 1-6 min (2.8 – 16.7 mHz)
1.8 MeV
3.4 MeV
Lpp
ULF
(flux)²/Hz
R_E^2/Hz
(mV/m)²/Hz
Frequency (10^{-7} Hz)
L = 2.5
L = 3.0
L = 3.5
L = 4.0
L = 4.5
L = 5.0
L = 5.5

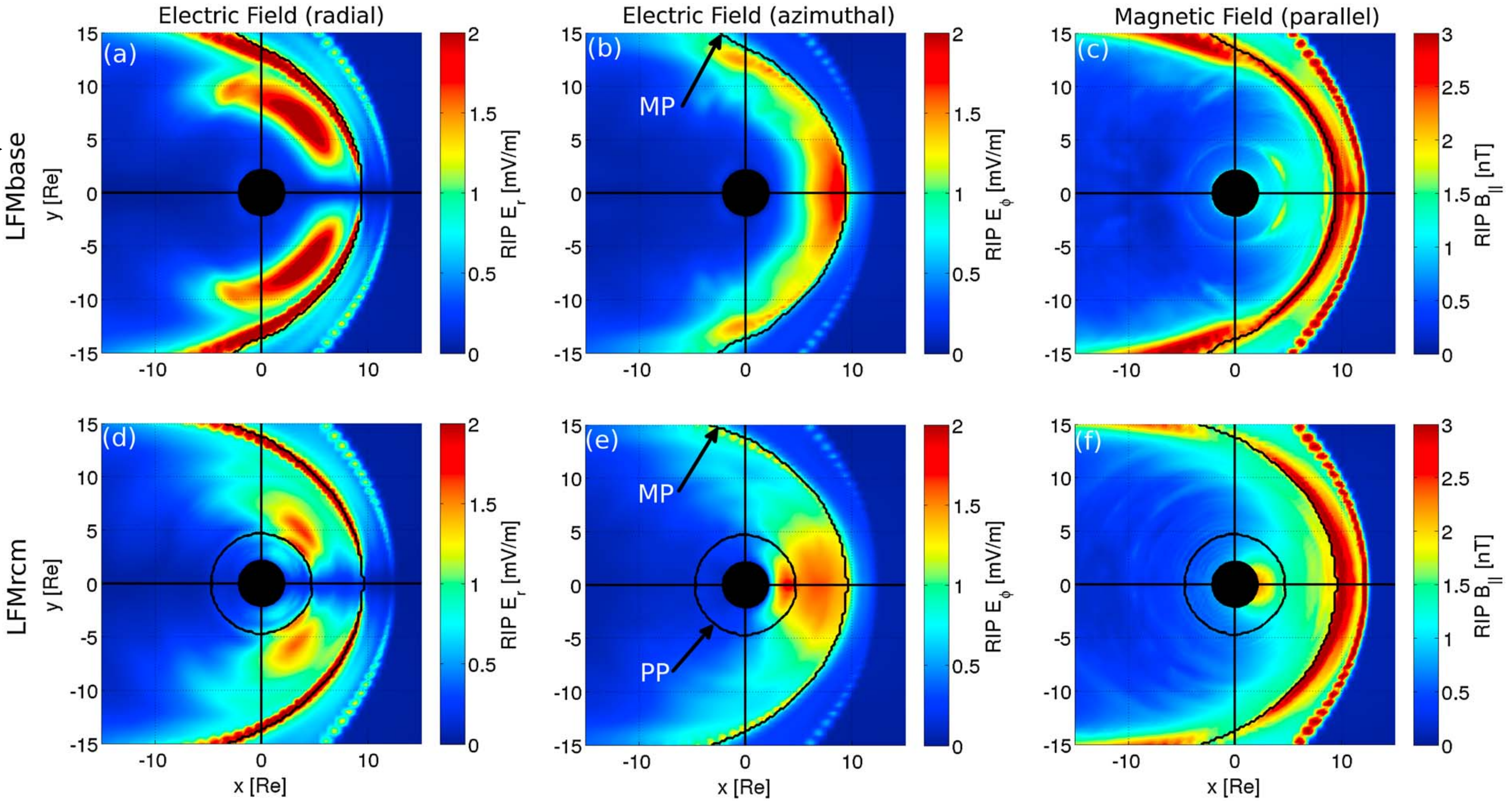
ULF and solar cycle influence on outer belt: assorted references

- Rostoker et al [1998] correlation between ULF and energetic electron flux at GOES 7. ULF power increases 1-2 days prior to the flux .
- Elkington et al [1999]: toroidal mode Pc 5 ULF can adiabatically accelerate energetic electrons.
- Mathie and Mann [2000]; O’Brien et al [2001]; Baker and Kanekal [2007]; show that Vsw > 450 km/s (or 500 km/s) correlate with enhanced energetic flux in the outer belt.
- O’Brien et al [2003] ; examines VLF and ULF, suggests that ULF is the main geoeffective driver at L > 5.
- Mann et al [2004]; ULF and Vsw have the highest correlation with the energetic electrons flux in the late declining phase.

Radial E field | Azimuthal E field | Parallel B field

Without plasmasphere →

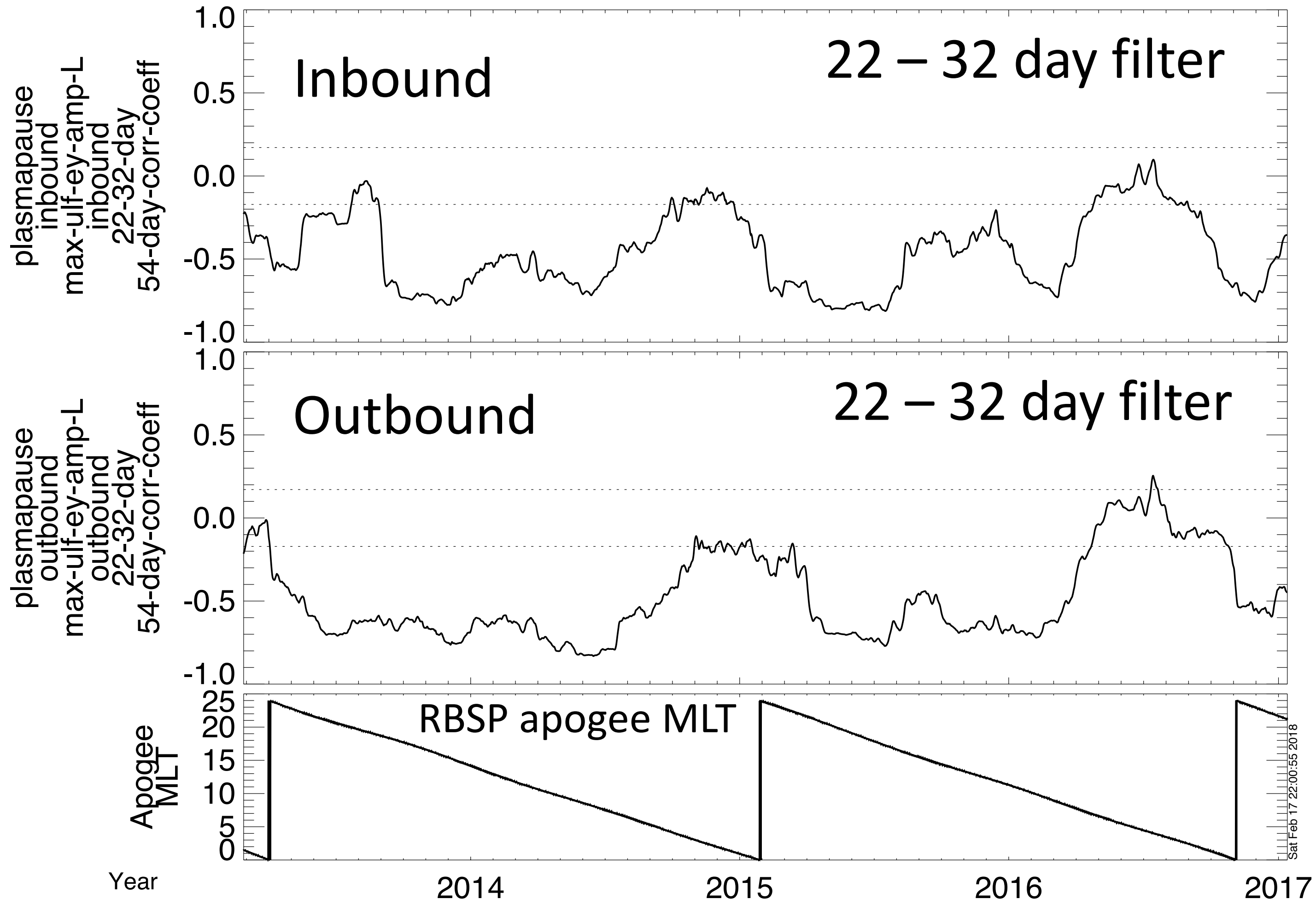
With plasmasphere →



Adapted from Claudepierre et al [2016] Fig. 3

MHD model showing simulated ULF (0.5 – 50 mHz; 20 - 2000 sec.) wave power distribution in the inner magnetosphere with and without an plasmasphere.

The L-value of the maximum ULF amplitude (Ey, 1-6 min, 2.8 – 16.7 mHz) and plasmapause L-value anti-correlate. Consistent with the results of Claudepierre et al [2016]



(Preliminary result)

Lpp (in bound) and L of max ULF (1-6 min) amp. Correlation coefficients for the 22-32 day filtered values.

Main Points (again)

- The plasmapause moves in and out at solar rotation periodicities (~27-days).
- By a significant amount: ~ 0.7 R_E on average.
- Driven by convection associated with CIRs.
- Most pronounced in the declining phase of the solar cycle.
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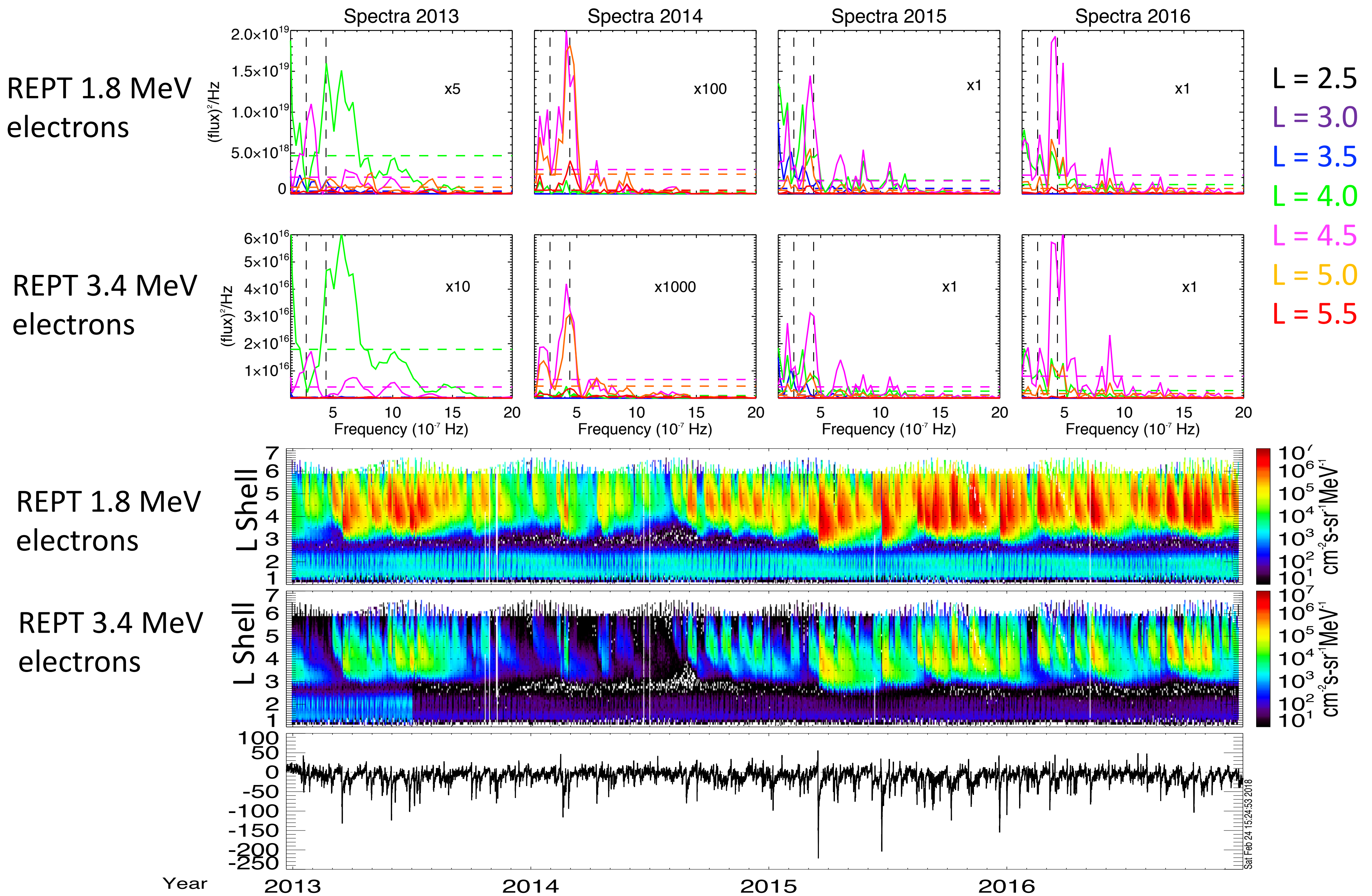
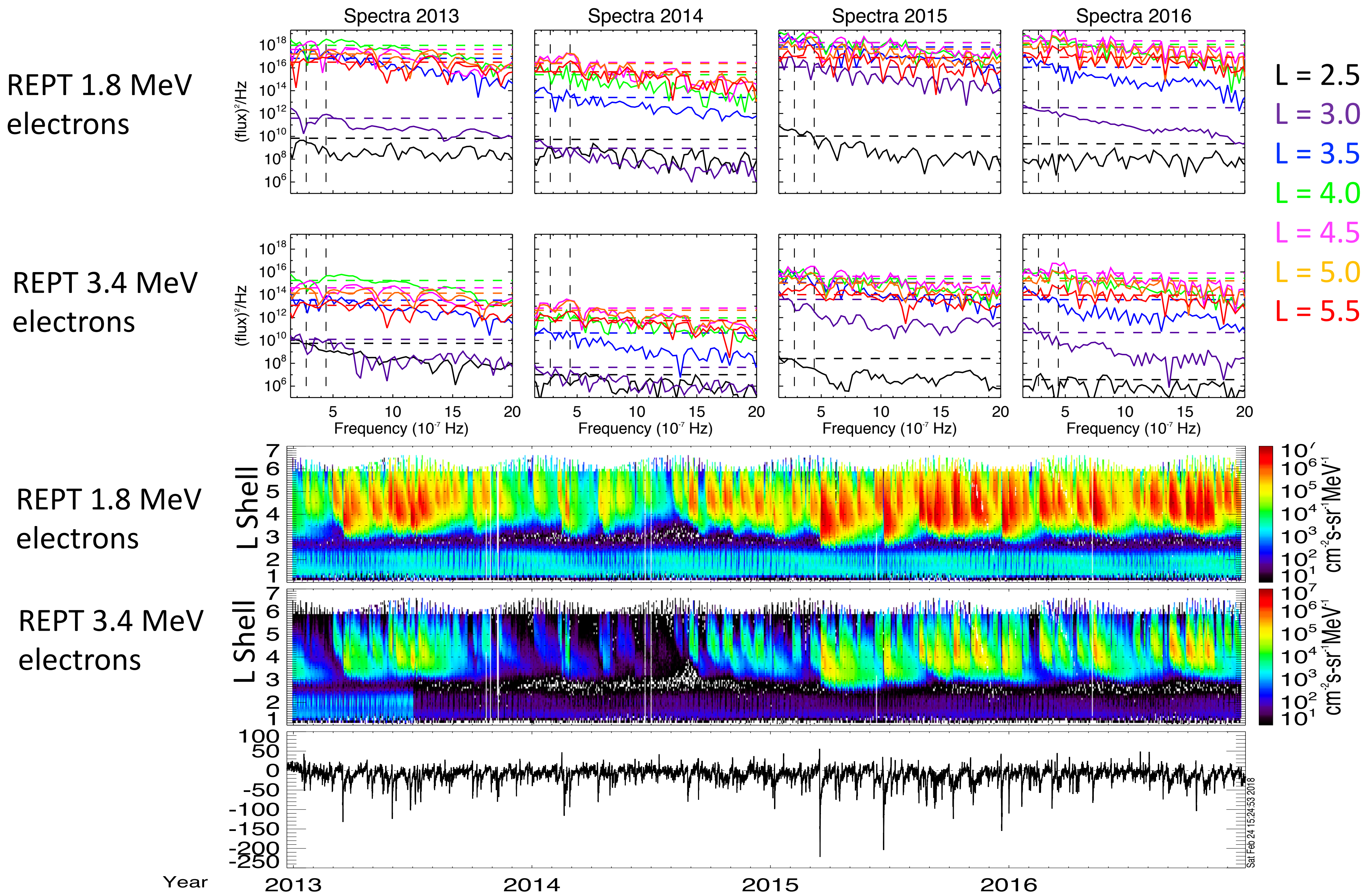
- ULF power also shows ~27-day variations; preliminary observations show anti-correlation in the L-value of max ULF amplitude with Lpp.

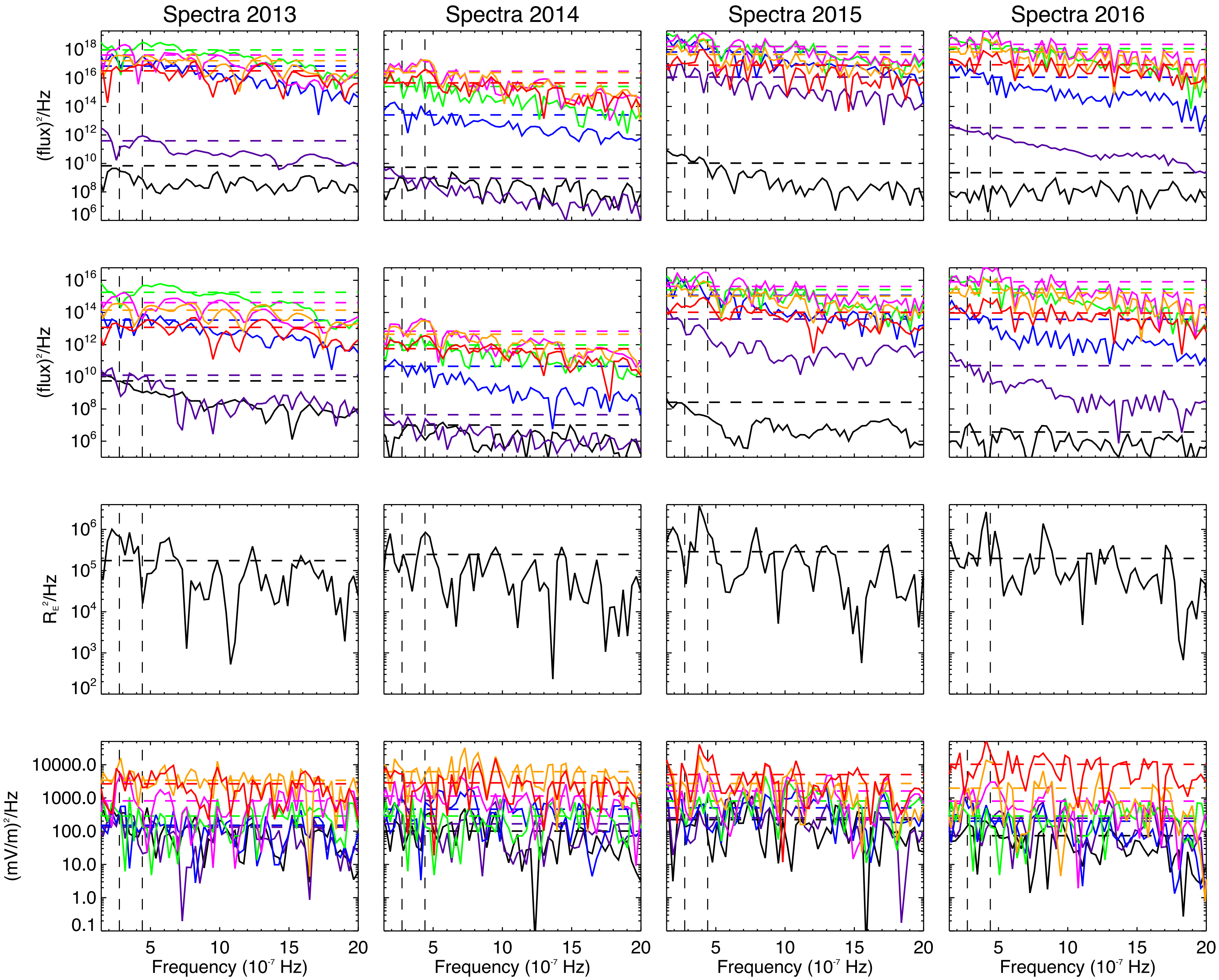
Extra slides

Van Allen Probes B REPT electrons (outbound)

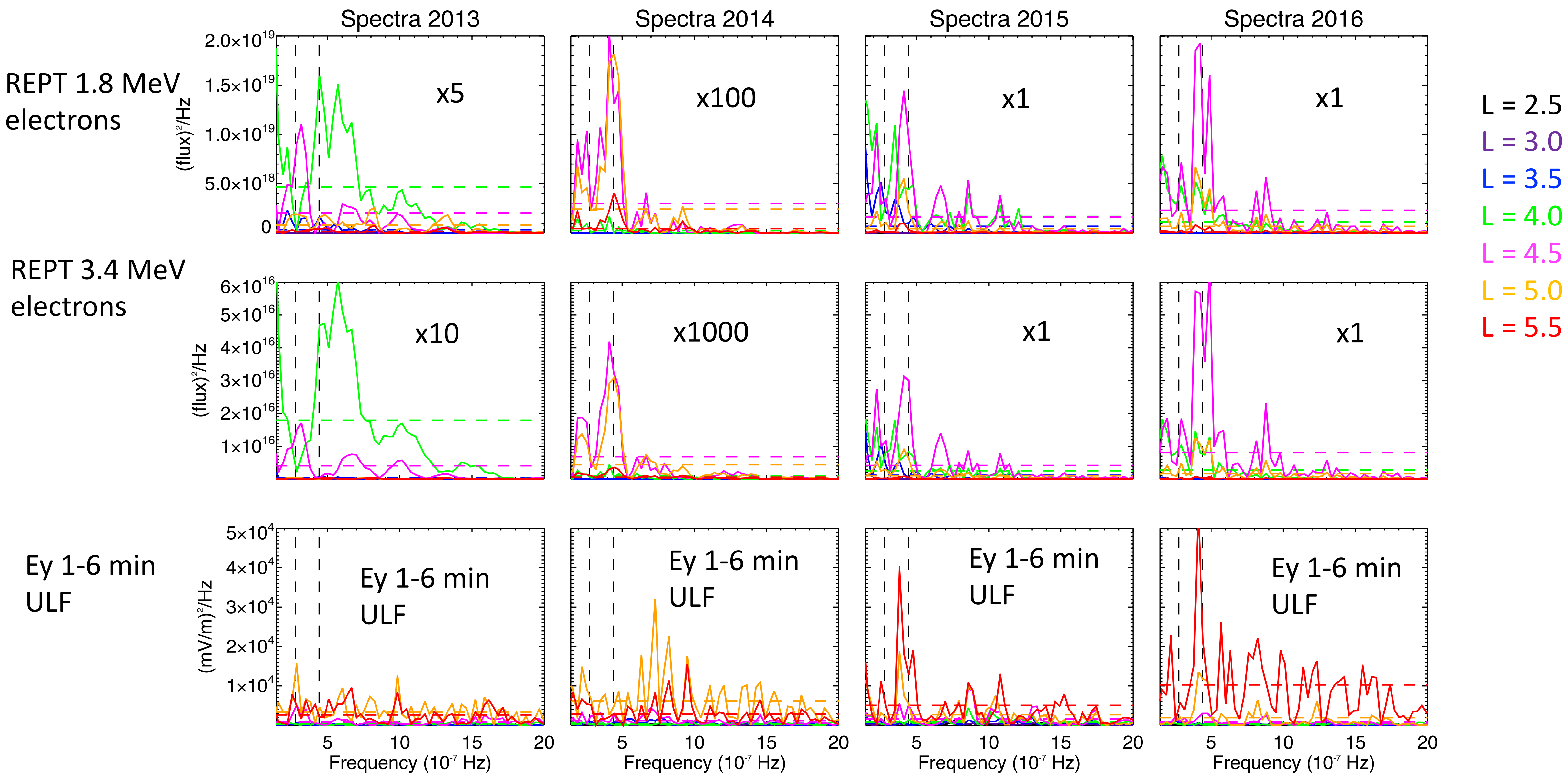


Van Allen Probes B REPT electrons (outbound)

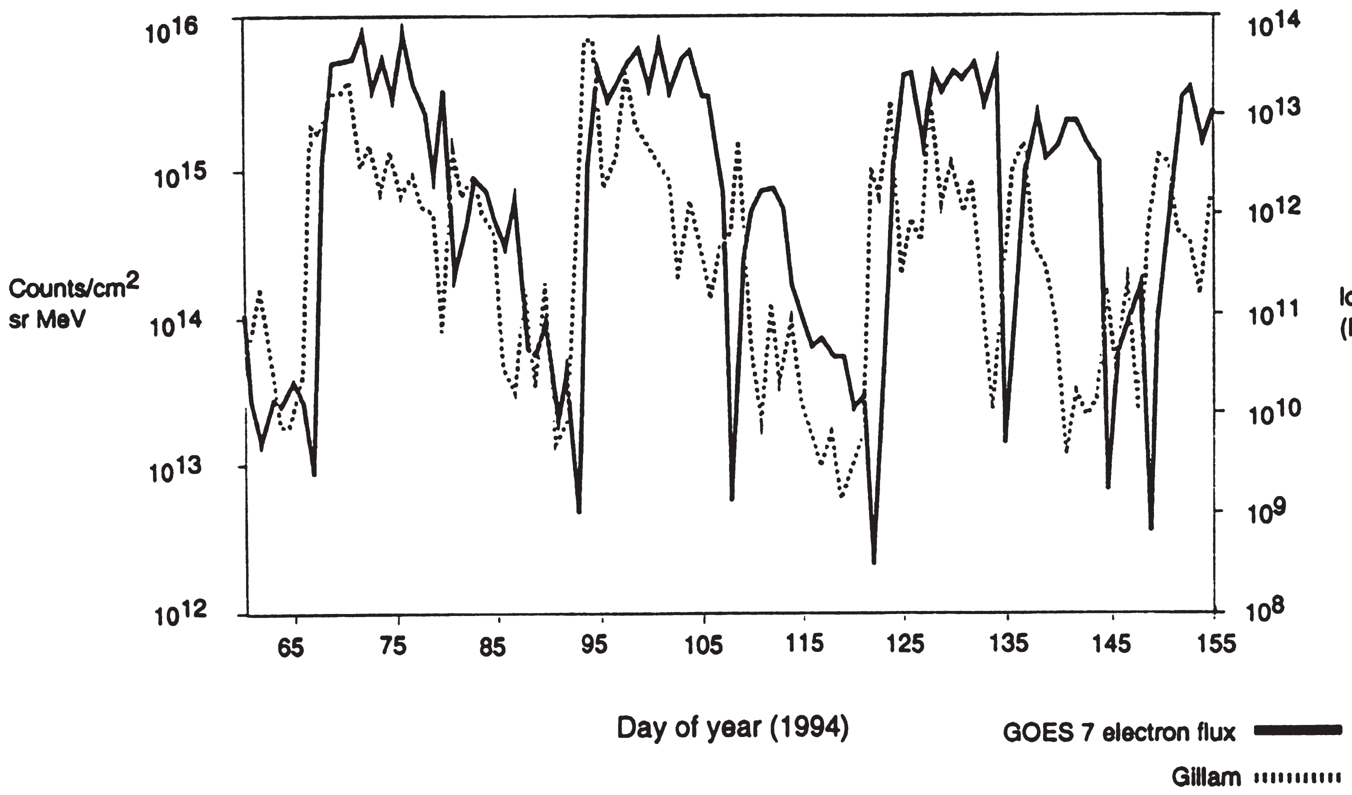




Spectra 2013
Spectra 2014
Spectra 2015
Spectra 2016
(flux)²/Hz
(flux)²/Hz
R_E²/Hz
(mV/m)²/Hz
Frequency (10⁻⁷ Hz)
Frequency (10⁻⁷ Hz)
Frequency (10⁻⁷ Hz)
Frequency (10⁻⁷ Hz)


Spectra 2013
Spectra 2014
Spectra 2015
Spectra 2016
REPT 1.8 MeV electrons
REPT 3.4 MeV electrons
Ey 1-6 min ULF
(flux)²/Hz
(mV/m)²/Hz
x5
x100
x1
x1
x10
x1000
x1
x1
Ey 1-6 min ULF
Ey 1-6 min ULF
Ey 1-6 min ULF
Ey 1-6 min ULF
Frequency (10⁻⁷ Hz)
L = 2.5
L = 3.0
L = 3.5
L = 4.0
L = 4.5
L = 5.0
L = 5.5

ULF waves power and outer belt flux have been shown to sometimes correlate.



Adapted from Rostoker et al. [1998] via Elkington [2006]

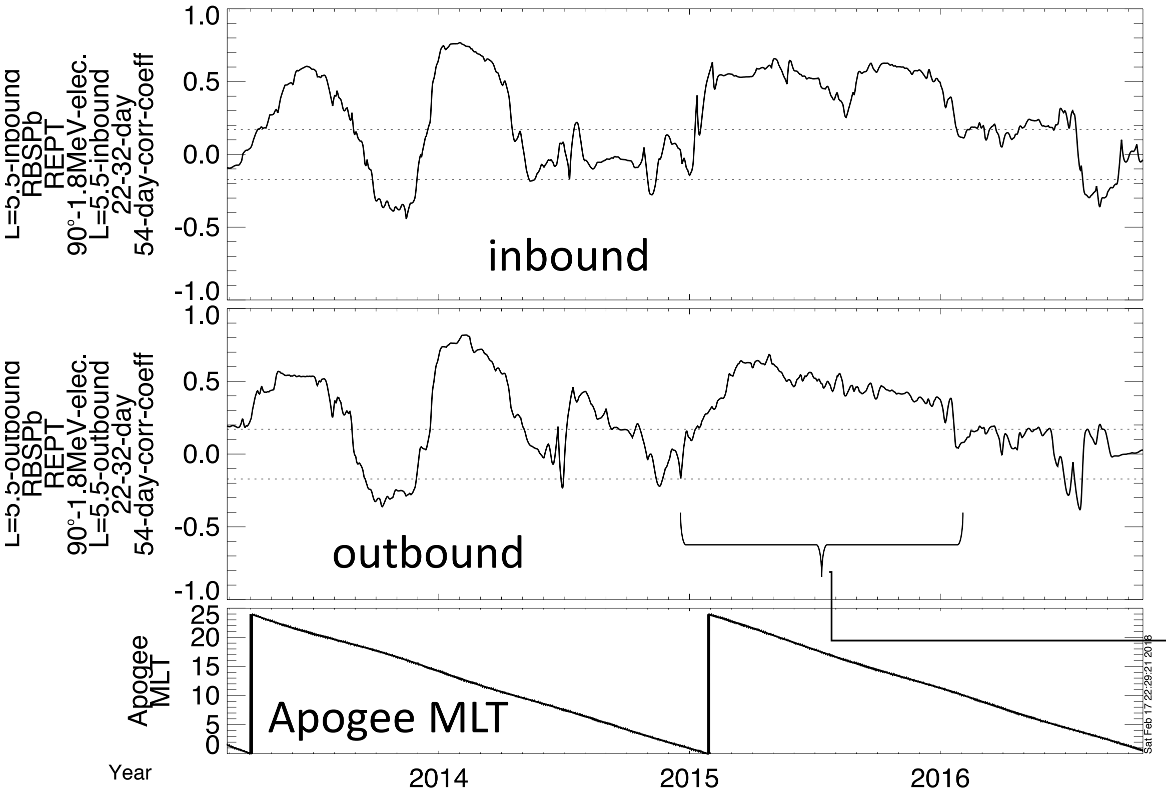
Rostoker et al. [1998] the increases in ULF and flux to encounters with high speed streams of solar wind.

Data from 1994, in the declining phase of the solar cycle.

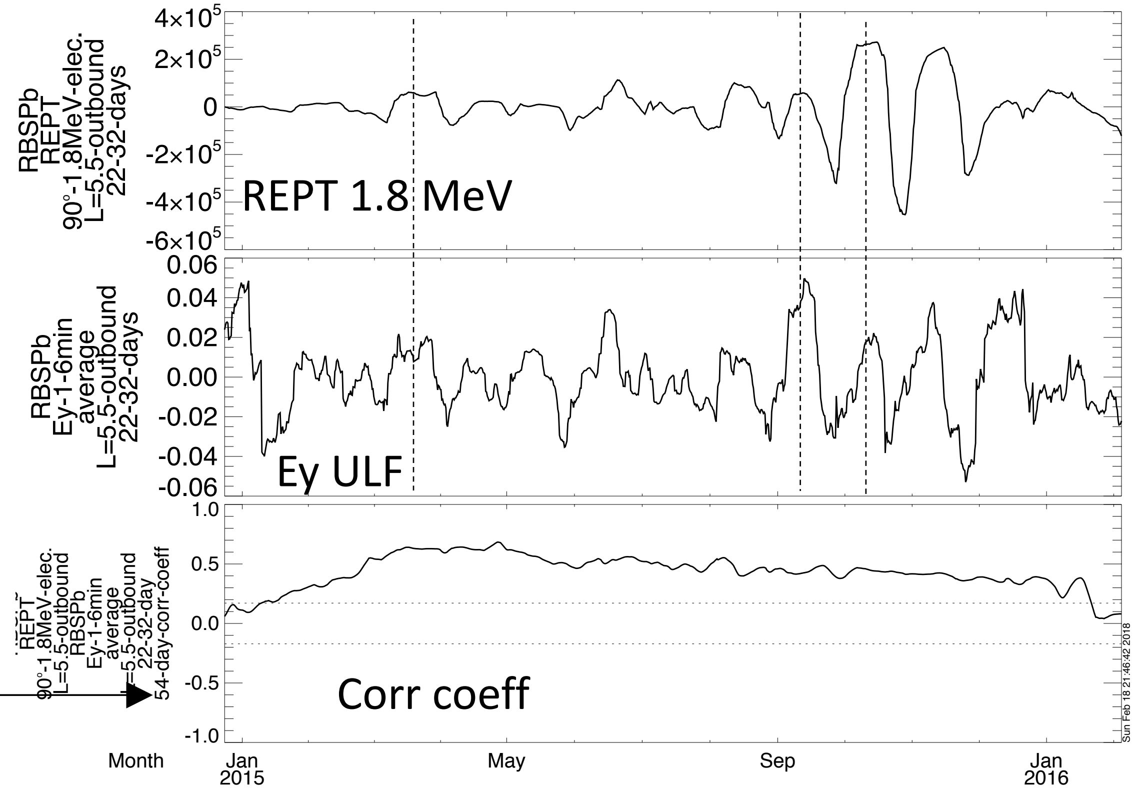
Note the ~ 27-day variation.

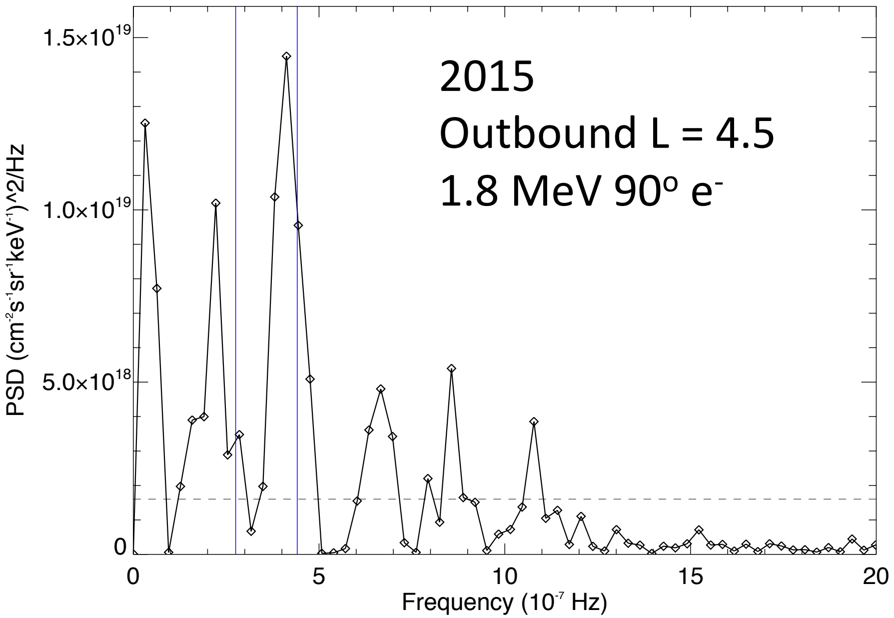
Correlation coefficients between Van Allen Probes B ULF amplitude (1-6 min Ey) and REPT 90^o 1.8 MeV at L = 5.5 [**Preliminary**]

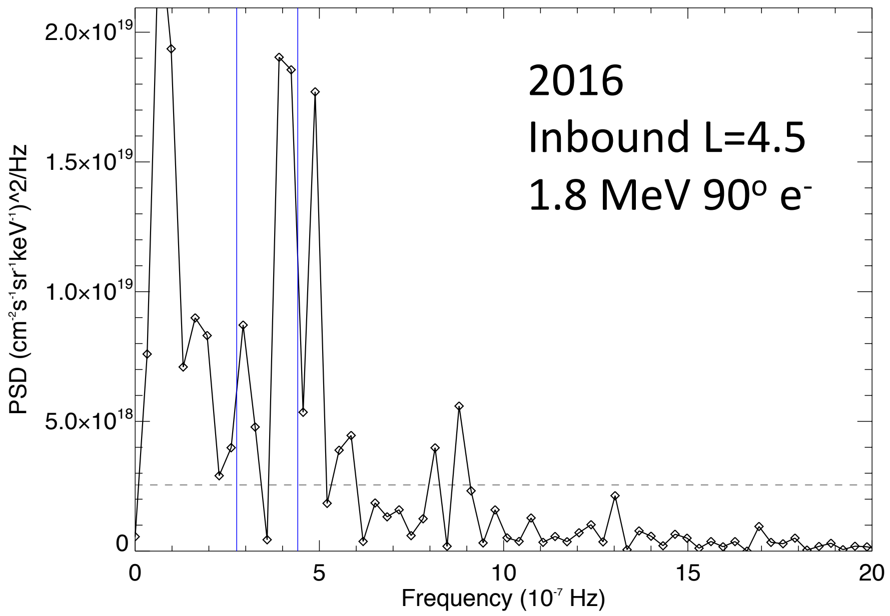
22-32 days filter, 54-day correlations

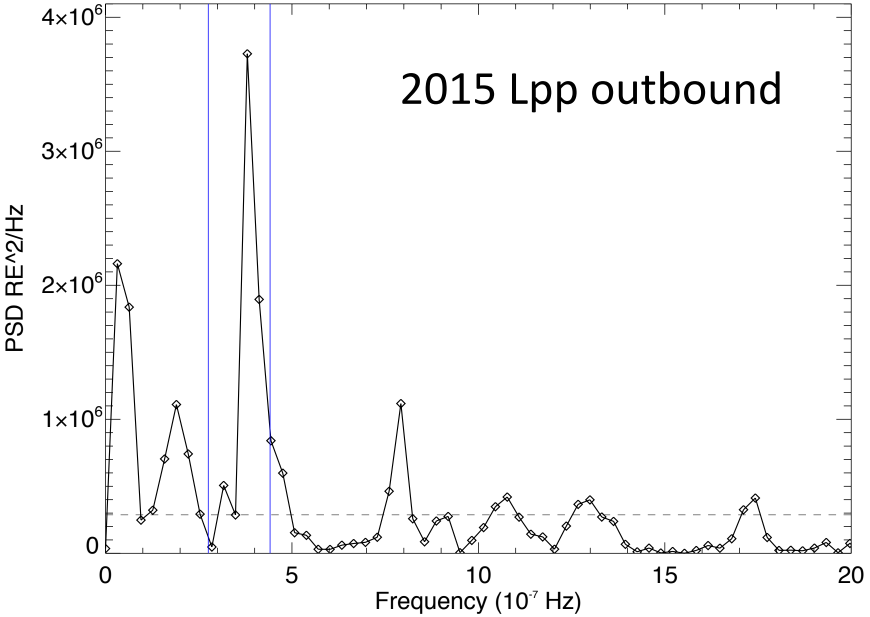


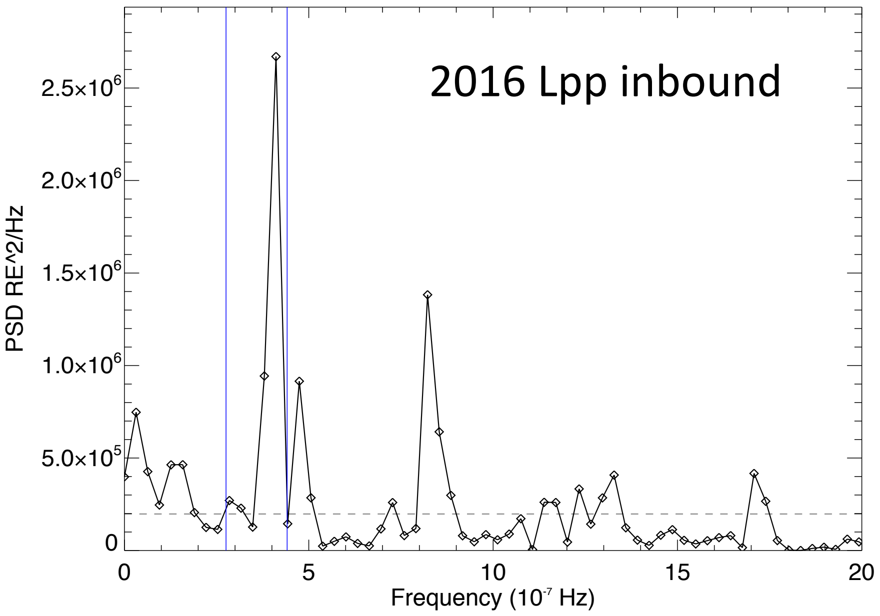
22-32 days filter

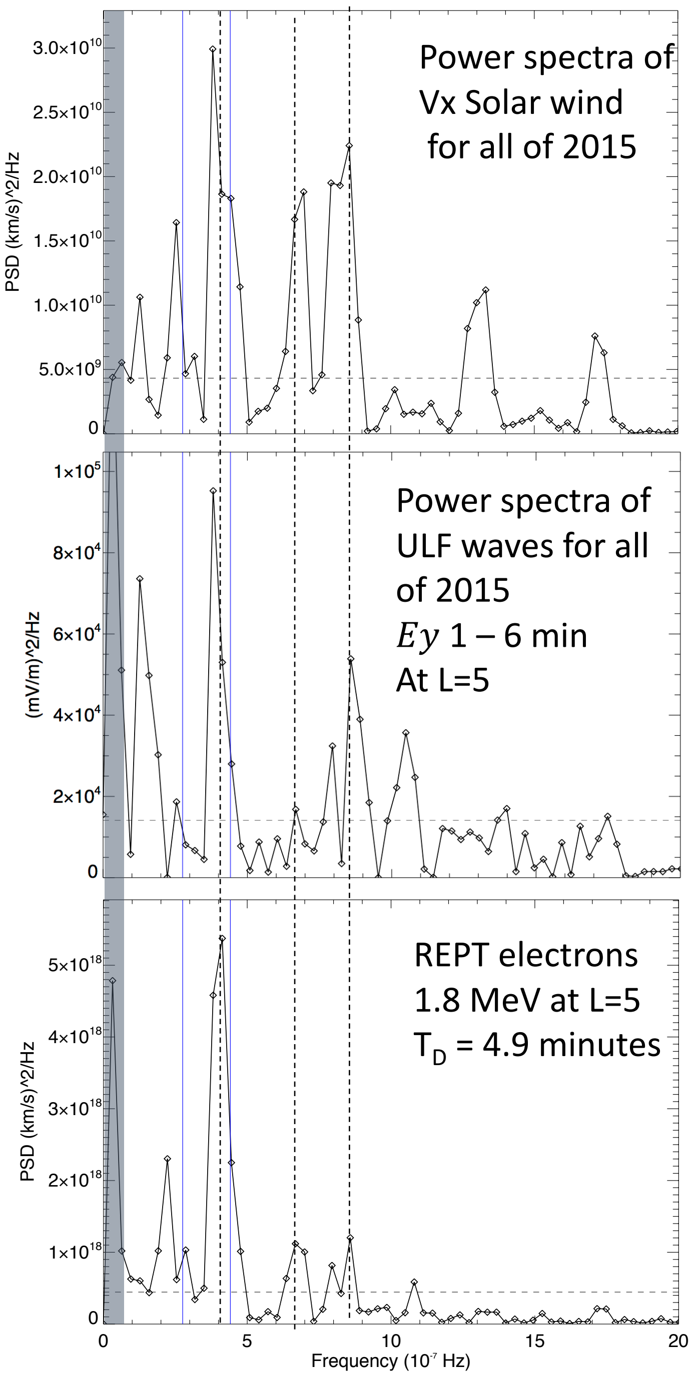


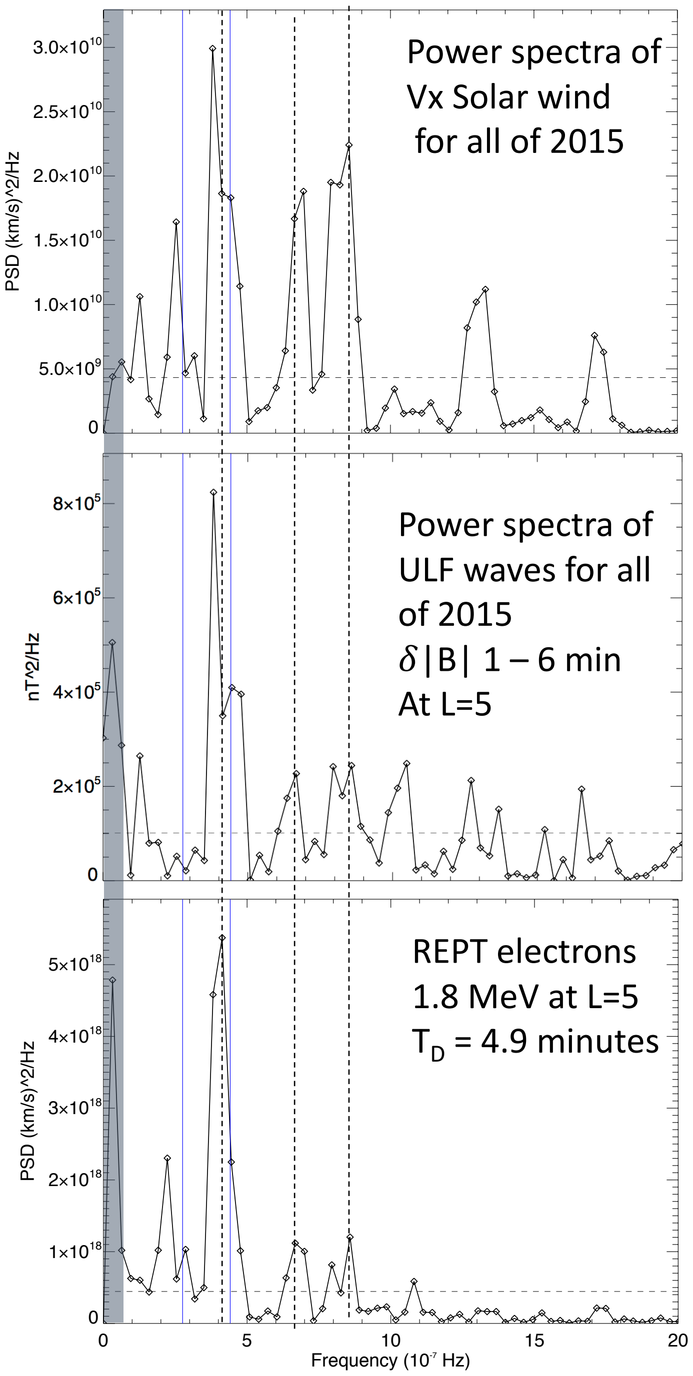

2015
Outbound L = 4.5
1.8 MeV 90° e⁻
PSD (cm⁻²s⁻¹sr⁻¹keV⁻¹)^2/Hz
Frequency (10⁻⁷ Hz)
1.5×10¹⁹
1.0×10¹⁹
5.0×10¹⁸
0
0
5
10
15
20


2016
Inbound L=4.5
1.8 MeV 90° e⁻
PSD (cm⁻²s⁻¹sr⁻¹keV⁻¹)^2/Hz
Frequency (10⁻⁷ Hz)
2.0×10¹⁹
1.5×10¹⁹
1.0×10¹⁹
5.0×10¹⁸
0
0
5
10
15
20


2015 Lpp outbound
PSD RE^2/Hz
Frequency (10⁻⁷ Hz)
4×10⁶
3×10⁶
2×10⁶
1×10⁶
0
0
5
10
15
20

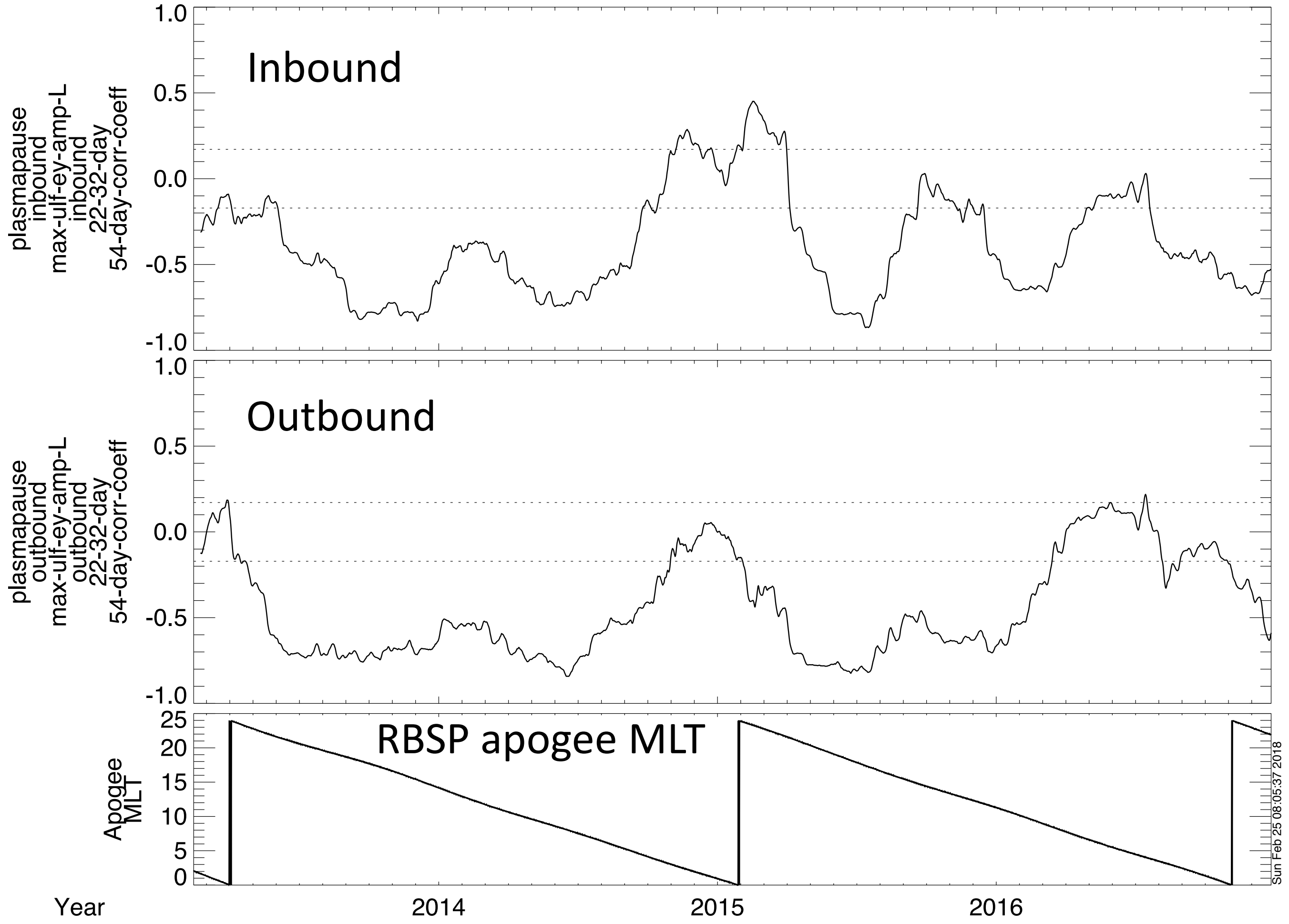

2016 Lpp inbound
PSD RE^2/Hz
Frequency (10⁻⁷ Hz)
2.5×10⁶
2.0×10⁶
1.5×10⁶
1.0×10⁶
5.0×10⁵
0
0
5
10
15
20


Power spectra of
Vx Solar wind
for all of 2015
PSD (km/s)^2/Hz
Power spectra of
ULF waves for all
of 2015
Ey 1 – 6 min
At L=5
(mV/m)^2/Hz
REPT electrons
1.8 MeV at L=5
T_D = 4.9 minutes
PSD (km/s)^2/Hz
Frequency (10⁻⁷ Hz)

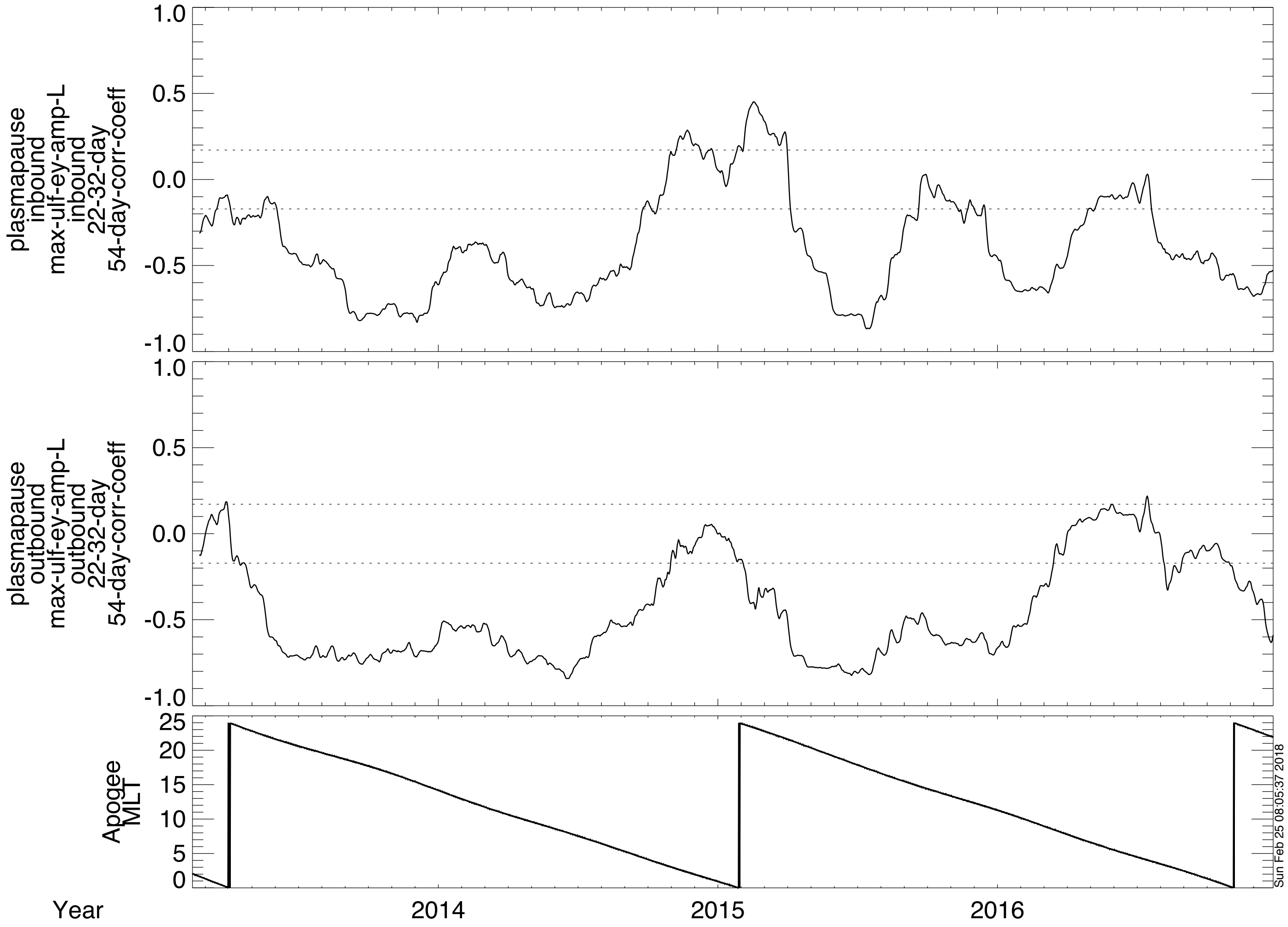

Power spectra of
Vx Solar wind
for all of 2015
PSD (km/s)^2/Hz
Power spectra of
ULF waves for all
of 2015
δ|B| 1 – 6 min
At L=5
nT^2/Hz
REPT electrons
1.8 MeV at L=5
T_D = 4.9 minutes
PSD (km/s)^2/Hz
Frequency (10⁻⁷ Hz)

The dayside anti-correlation between the L-value of maximum ULF amplitude and Lpp is consistent with the results of Claudepierre et al [2016]

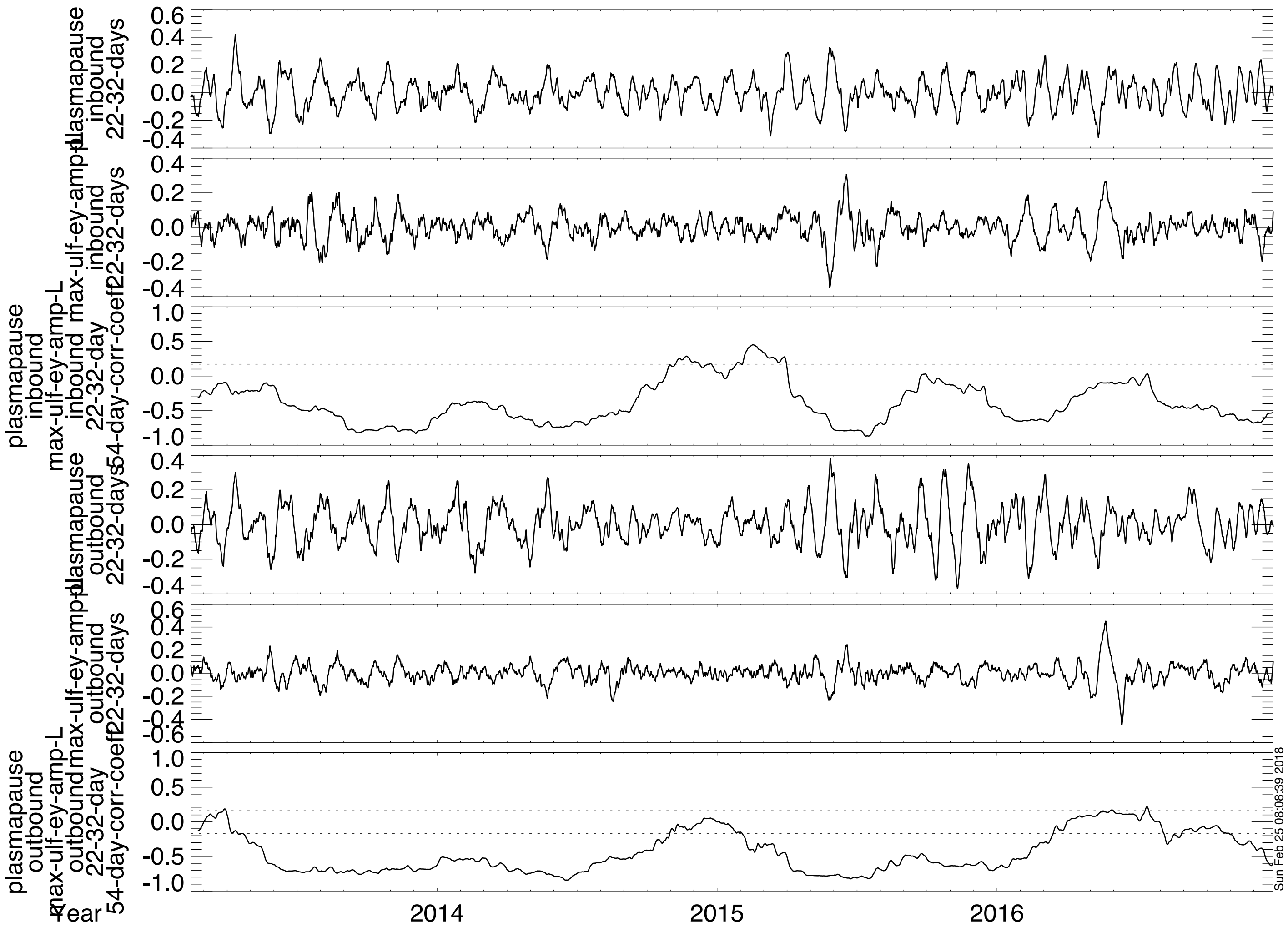
(Preliminary result)



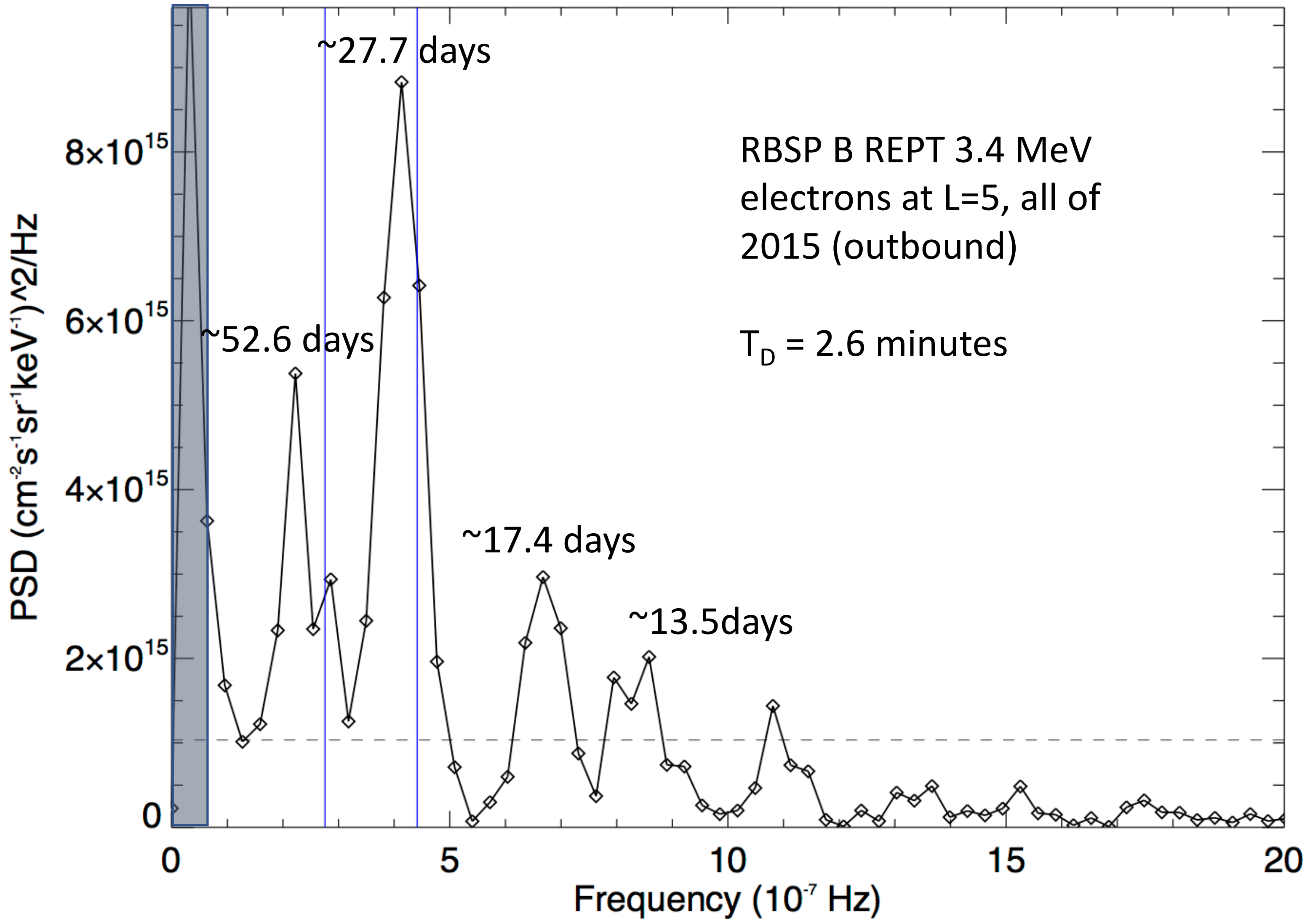
Lpp (in bound) and L of max ULF (1-6 min) amp. Correlation coefficients for the 22-32 day filtered values.



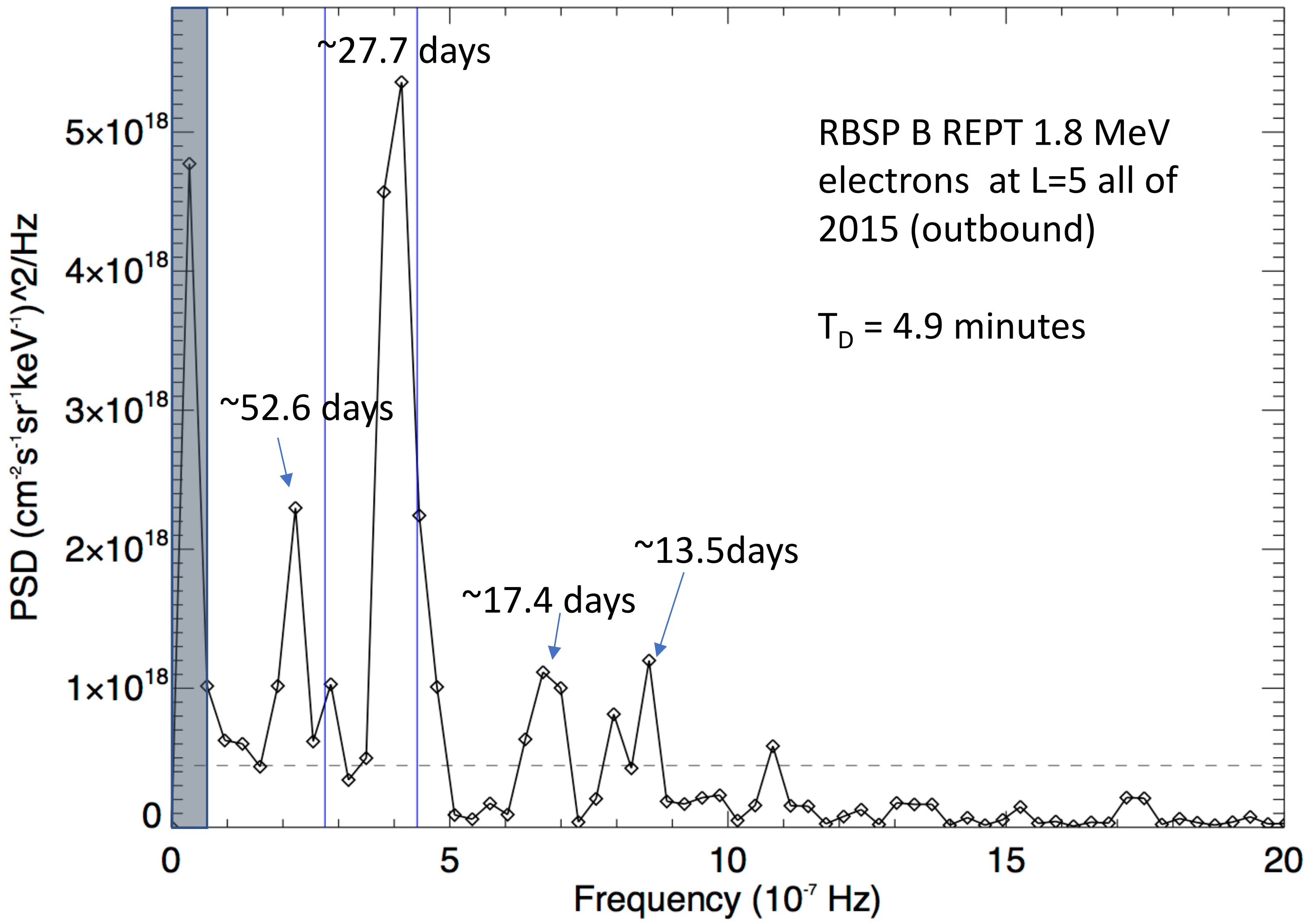
plasmapause
inbound
max-ulf-ey-amp-L
inbound
22-32-day
54-day-corr-coeff
1.0
0.5
0.0
-0.5
-1.0
plasmapause
outbound
max-ulf-ey-amp-L
outbound
22-32-day
54-day-corr-coeff
1.0
0.5
0.0
-0.5
-1.0
Apogee
MLT
25
20
15
10
5
0
Year
2014
2015
2016
Sun Feb 25 08:05:37 2018



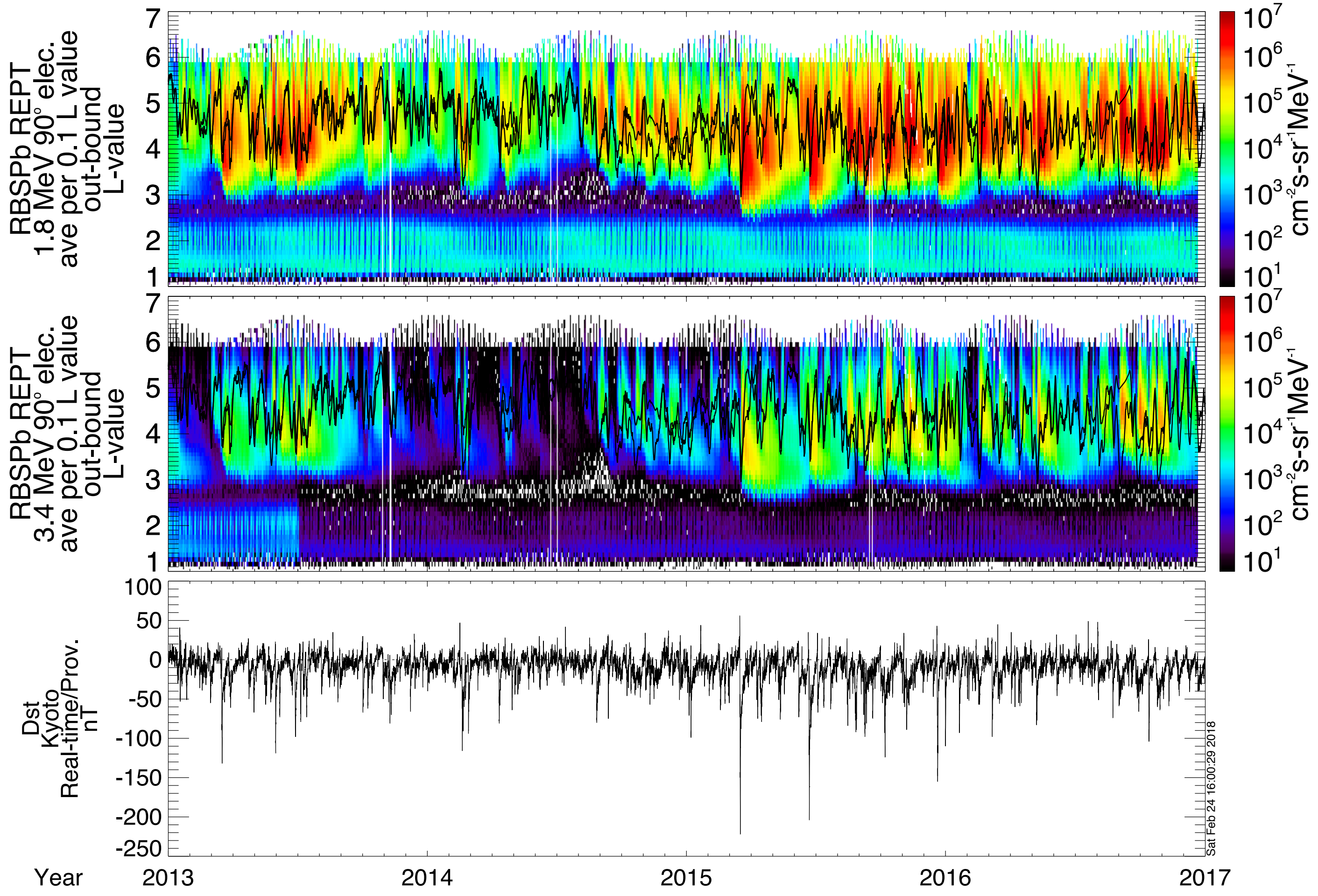
plasmapause
inbound
22-32-days
max-ulf-ey-amp-L
inbound
22-32-days
plasmapause
inbound
max-ulf-ey-amp-L
inbound
22-32-day
54-day-corr-coeff
plasmapause
outbound
22-32-days
max-ulf-ey-amp-L
outbound
22-32-days
plasmapause
outbound
max-ulf-ey-amp-L
outbound
22-32-day
54-day-corr-coeff
Year
2014
2015
2016
Sun Feb 25 08:08:39 2018



We observe significant variations in 3.4 MeV electron flux intensity at L = 5 at solar rotation periods in 2015

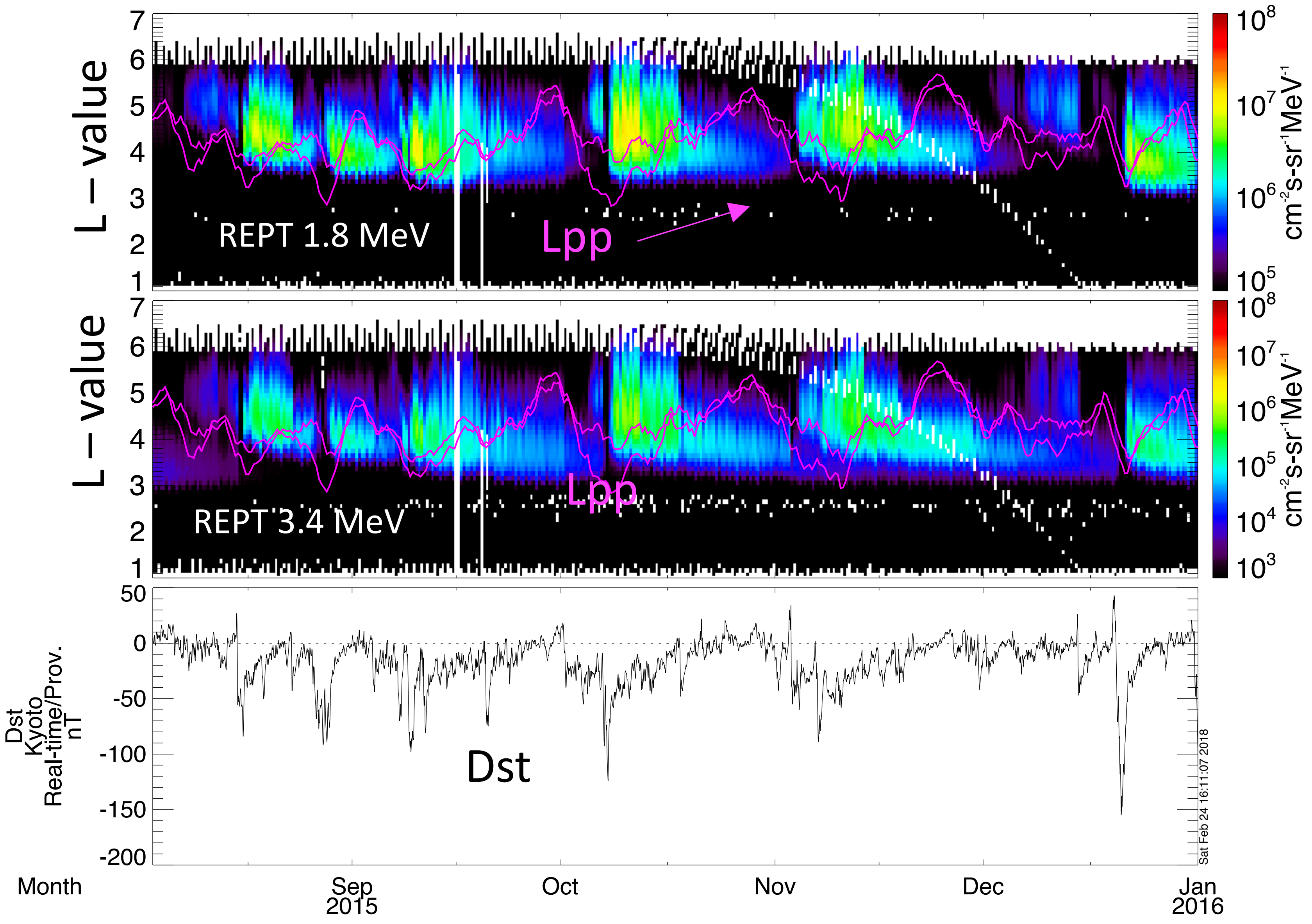


We observe significant variations in 1.8 MeV electron flux intensity at L = 5 at solar rotation periods in 2015


RBSPb REPT
1.8 MeV 90° elec.
ave per 0.1 L value
out-bound
L-value
RBSPb REPT
3.4 MeV 90° elec.
ave per 0.1 L value
out-bound
L-value
cm-2-s-sr-1MeV-1
Dst
Kyoto
Real-time/Prov.
nT
Year
2013
2014
2015
2016
2017
Sat Feb 24 16:00:29 2018

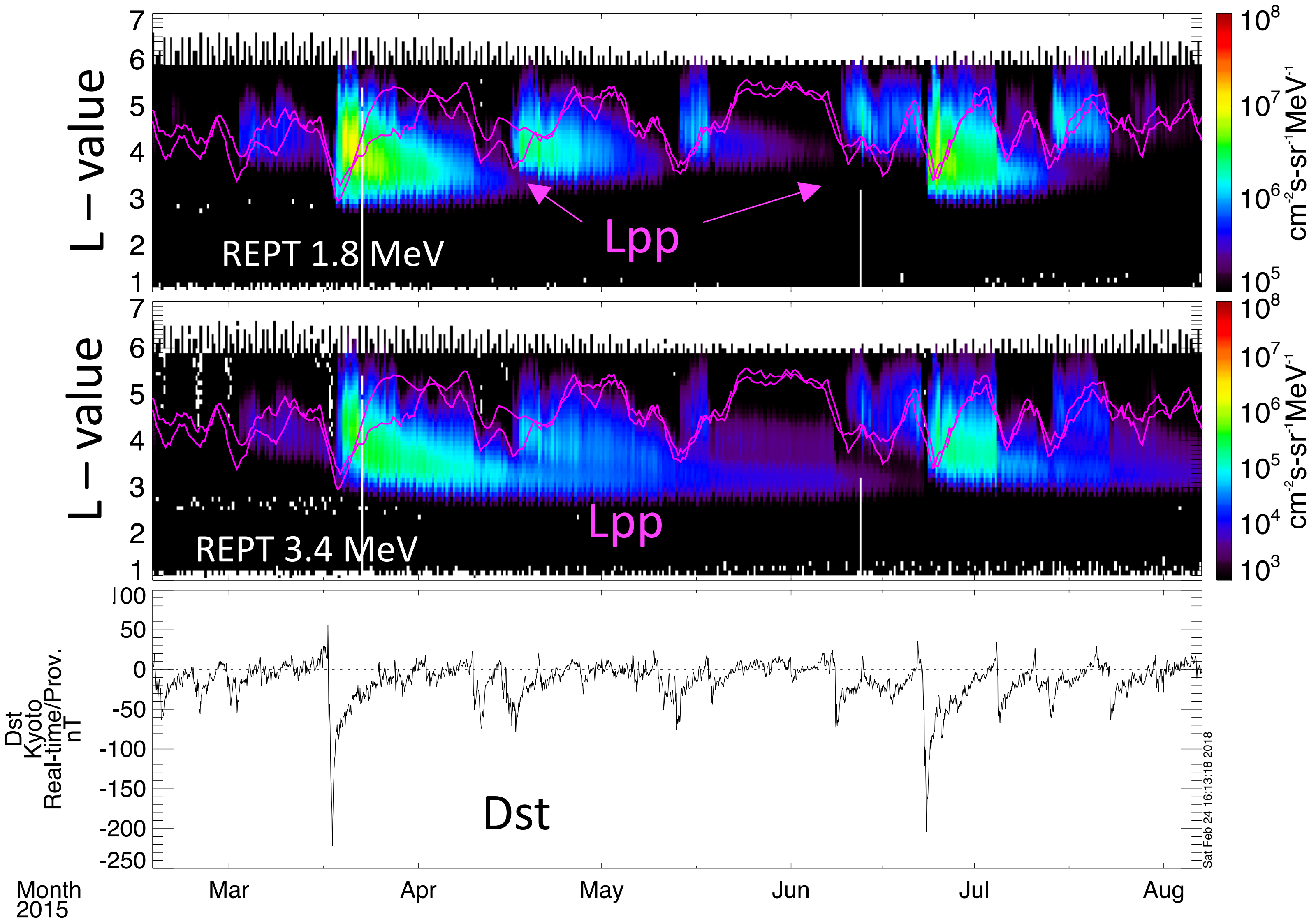
Van Allen Probes B REPT 1.8, 3.4 MeV electrons 2015

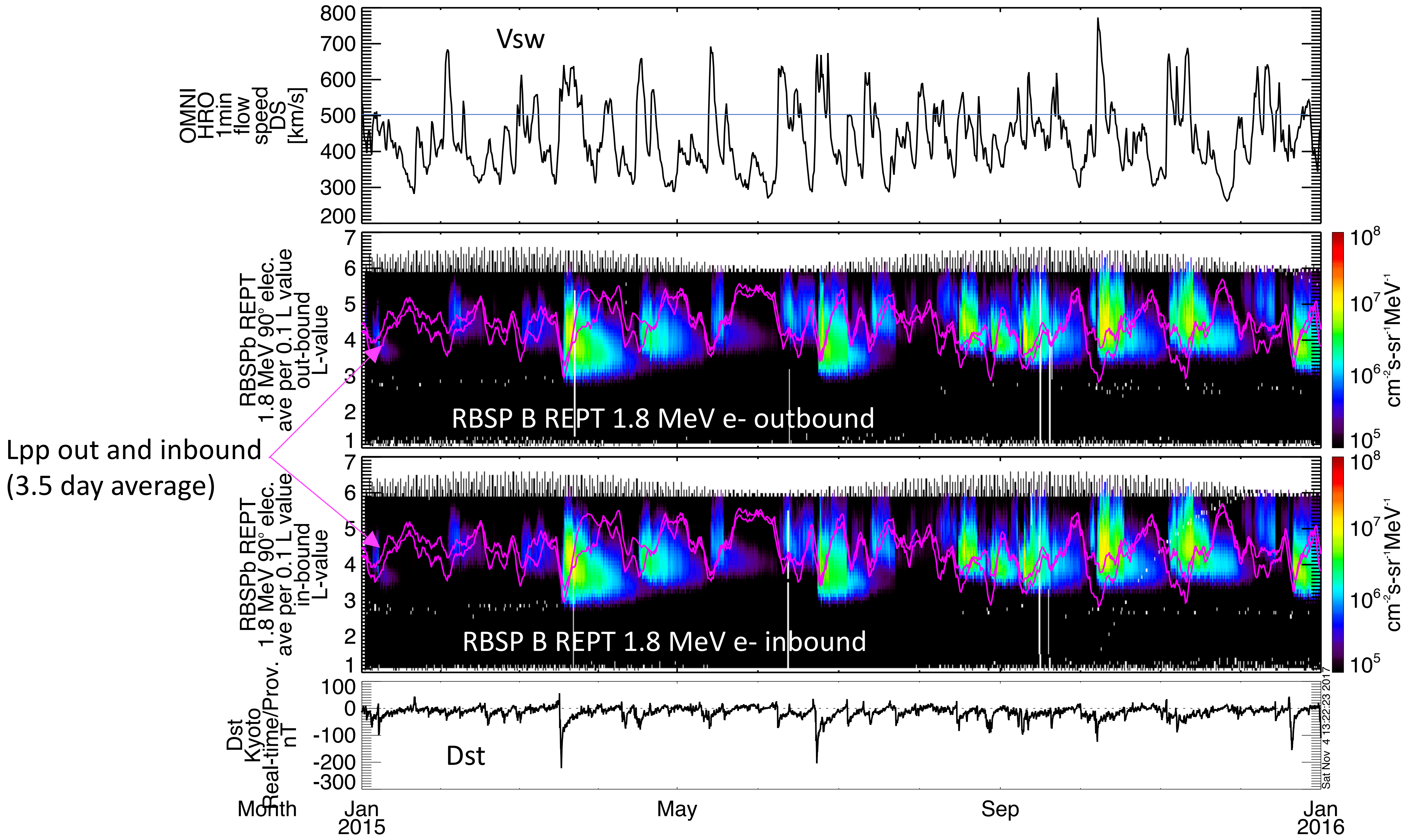
Note that the plasmasphere is often overlaying a significant fraction of the outer belt

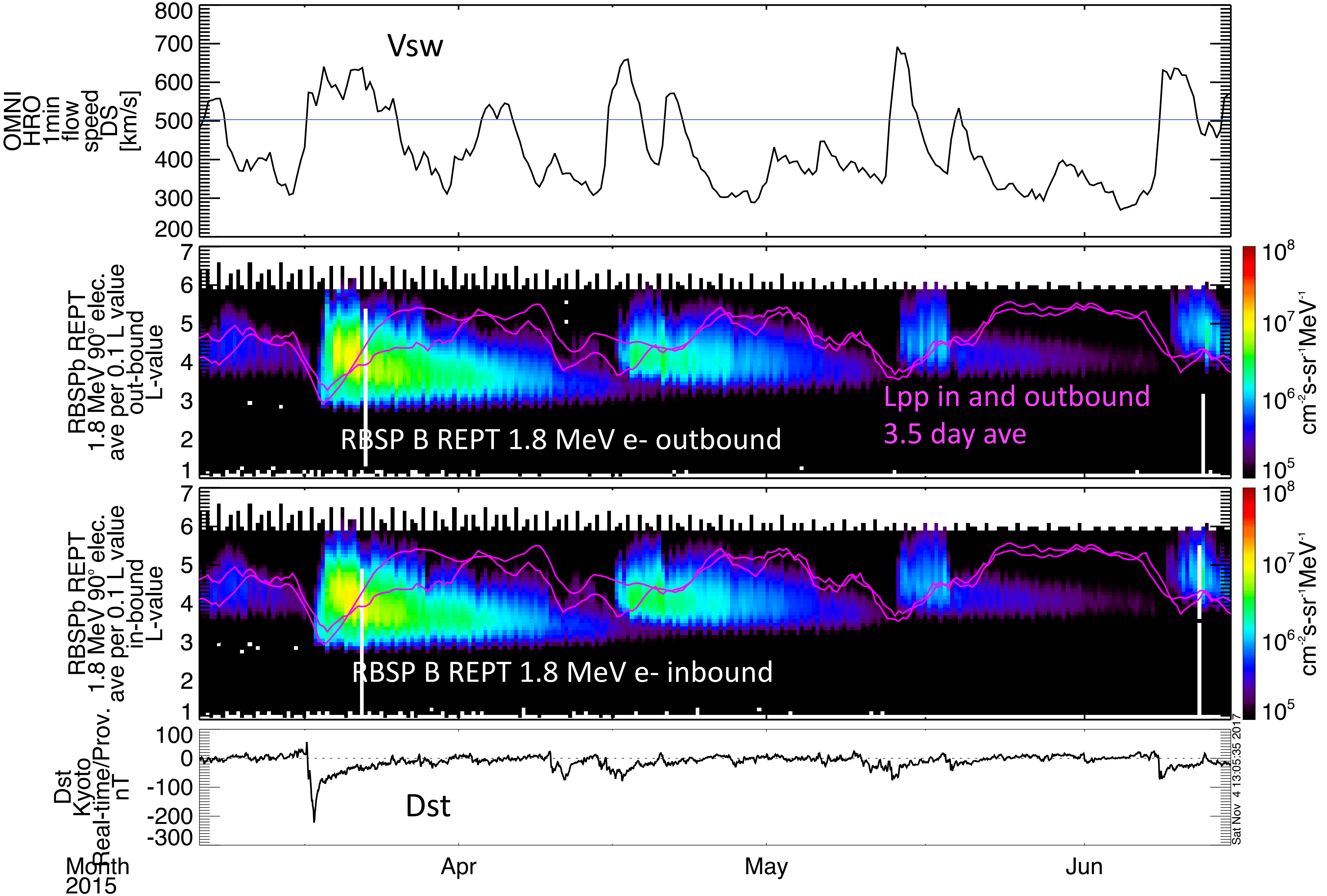


Van Allen Probes B REPT 1.8, 3.4 MeV electrons 2015

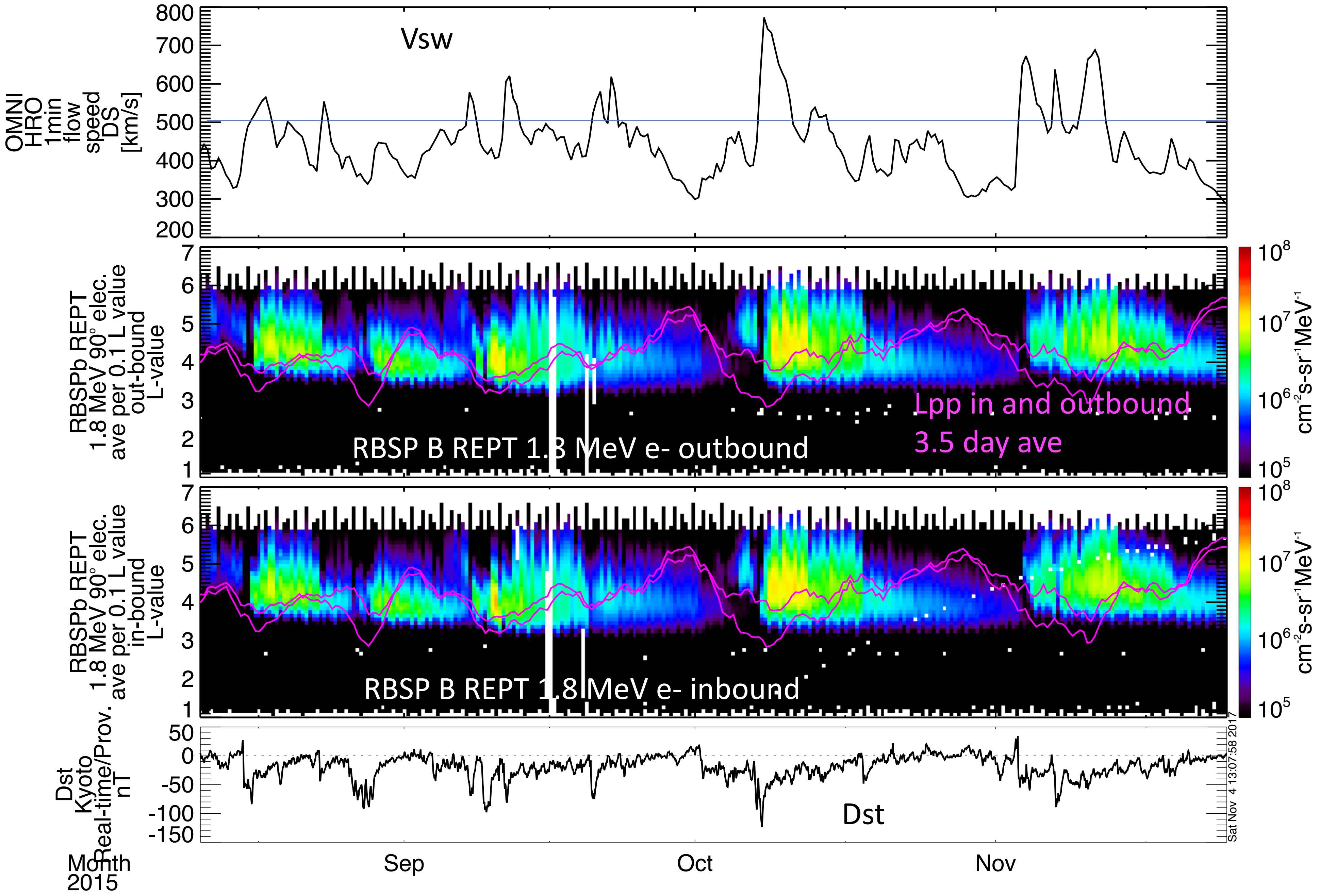
Note that the plasmasphere is often overlaying a significant fraction of the outer belt




Vsw
OMNI HRO 1min flow speed DS [km/s]
800
700
600
500
400
300
200
RBSPb REPT 1.8 MeV 90° elec. ave per 0.1 L value out-bound L-value
RBSP B REPT 1.8 MeV e- outbound
Lpp out and inbound
(3.5 day average)
RBSPb REPT 1.8 MeV 90° elec. ave per 0.1 L value in-bound L-value
RBSP B REPT 1.8 MeV e- inbound
7
6
5
4
3
2
1
10^8
10^7
10^6
10^5
$cm^{-2}s\text{-}sr^{-1}MeV^{-1}$
Dst Kyoto Real-time/Prov. nT
Dst
100
0
-100
-200
-300
Month
Jan 2015
May
Sep
Jan 2016
Sat Nov 4 13:22:23 2017

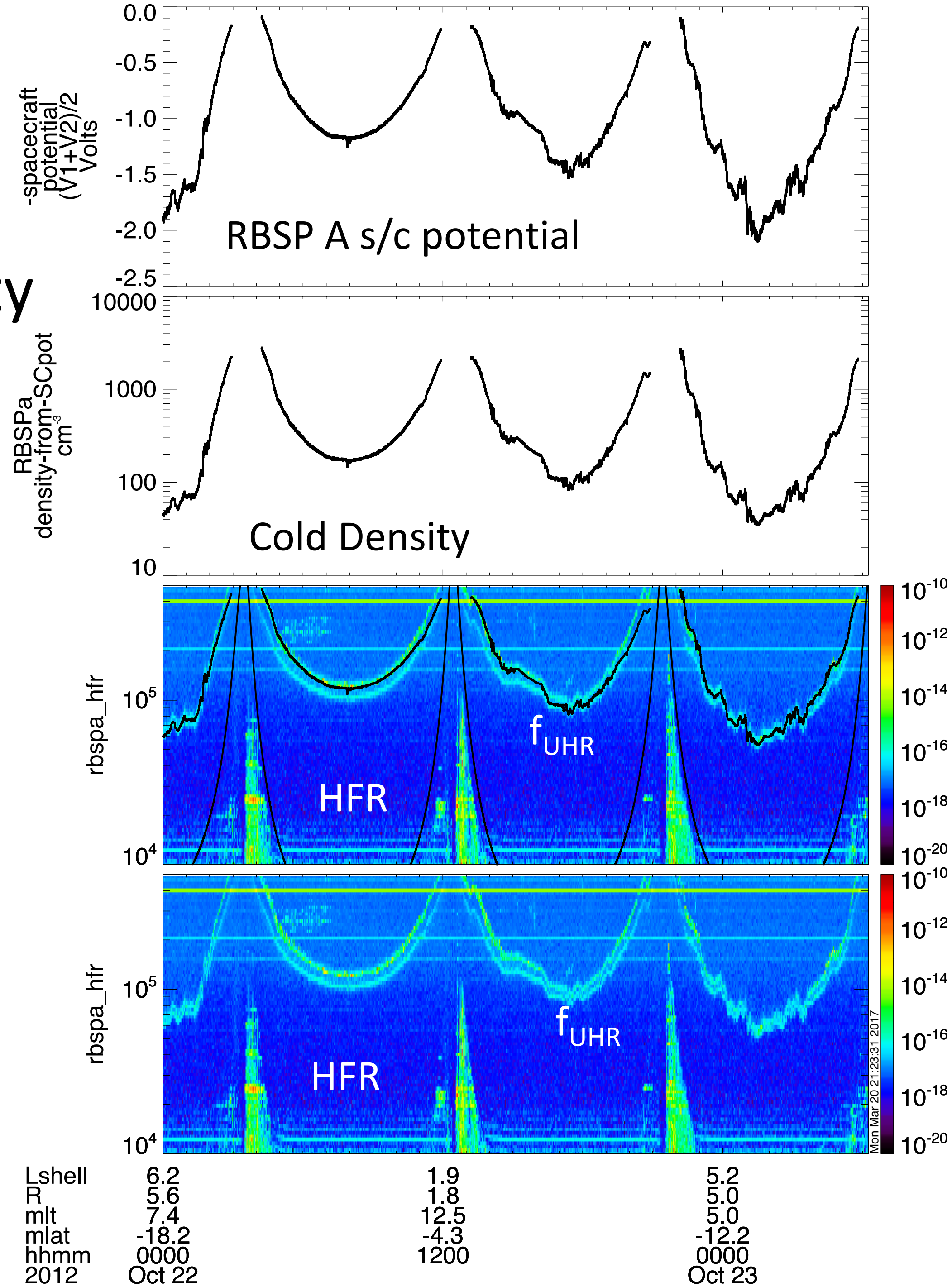


Vsw
OMNI HRO 1min flow speed DS [km/s]
RBSPb REPT 1.8 MeV 90° elec. ave per 0.1 L value out-bound L-value
RBSP B REPT 1.8 MeV e- outbound
Lpp in and outbound
3.5 day ave
RBSPb REPT 1.8 MeV 90° elec. ave per 0.1 L value in-bound L-value
RBSP B REPT 1.8 MeV e- inbound
cm⁻²s⁻sr⁻¹MeV⁻¹
Dst Kyoto Real-time/Prov. nT
Dst
Month 2015
Apr
May
Jun
Sat Nov 4 13:05:35 2017



Vsw
OMNI HRO 1min flow speed DS [km/s]
RBSPb REPT 1.8 MeV 90° elec. ave per 0.1 L value out-bound L-value
RBSP B REPT 1.8 MeV e- outbound
Lpp in and outbound
3.5 day ave
RBSPb REPT 1.8 MeV 90° elec. ave per 0.1 L value in-bound L-value
RBSP B REPT 1.8 MeV e- inbound
cm-2s-sr-1MeV-1
Dst Kyoto Real-time/Prov. nT
Dst
Month 2015
Sep
Oct
Nov
Sat Nov 4 13:07:58 2017

Determination of cold plasma density from spacecraft potential.



$$f_{UHR}^2 = f_{pe}^2 + f_{ce}^2$$

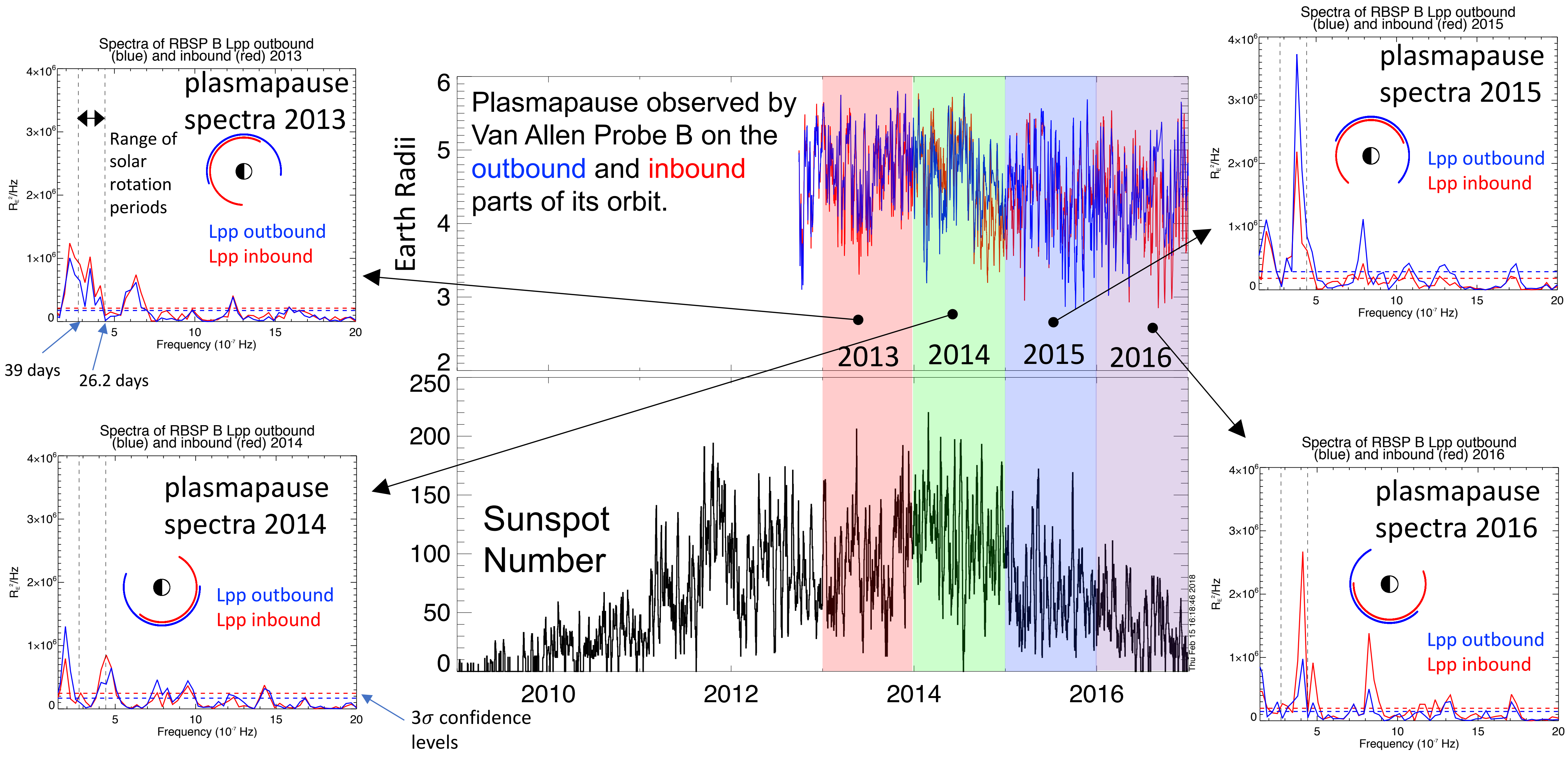
$$f_{ce} = \frac{1}{2\pi}\left(\frac{eB}{m_e}\right)$$

$$f_{pe} = \frac{1}{2\pi}\sqrt{\frac{n_e e^2}{m_e \epsilon_0}}$$

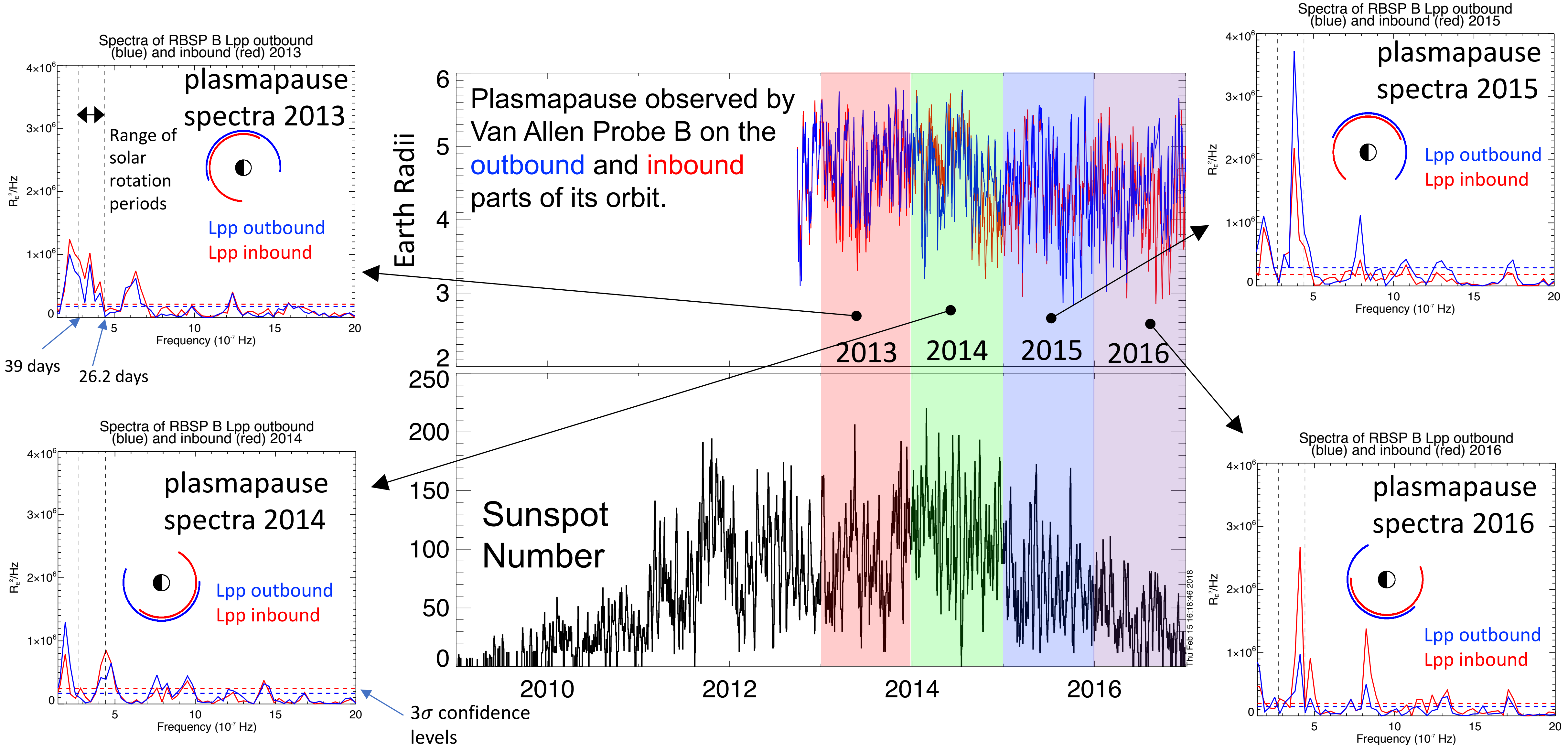
$$I_{bias} + I_{ph}(v_{sc}) + I_{th}(n_e, v_{sc}) = 0$$

$$n_e = n_1 e^{\frac{v_{sc}}{v_1}} + n_2 e^{\frac{v_{sc}}{v_2}}$$

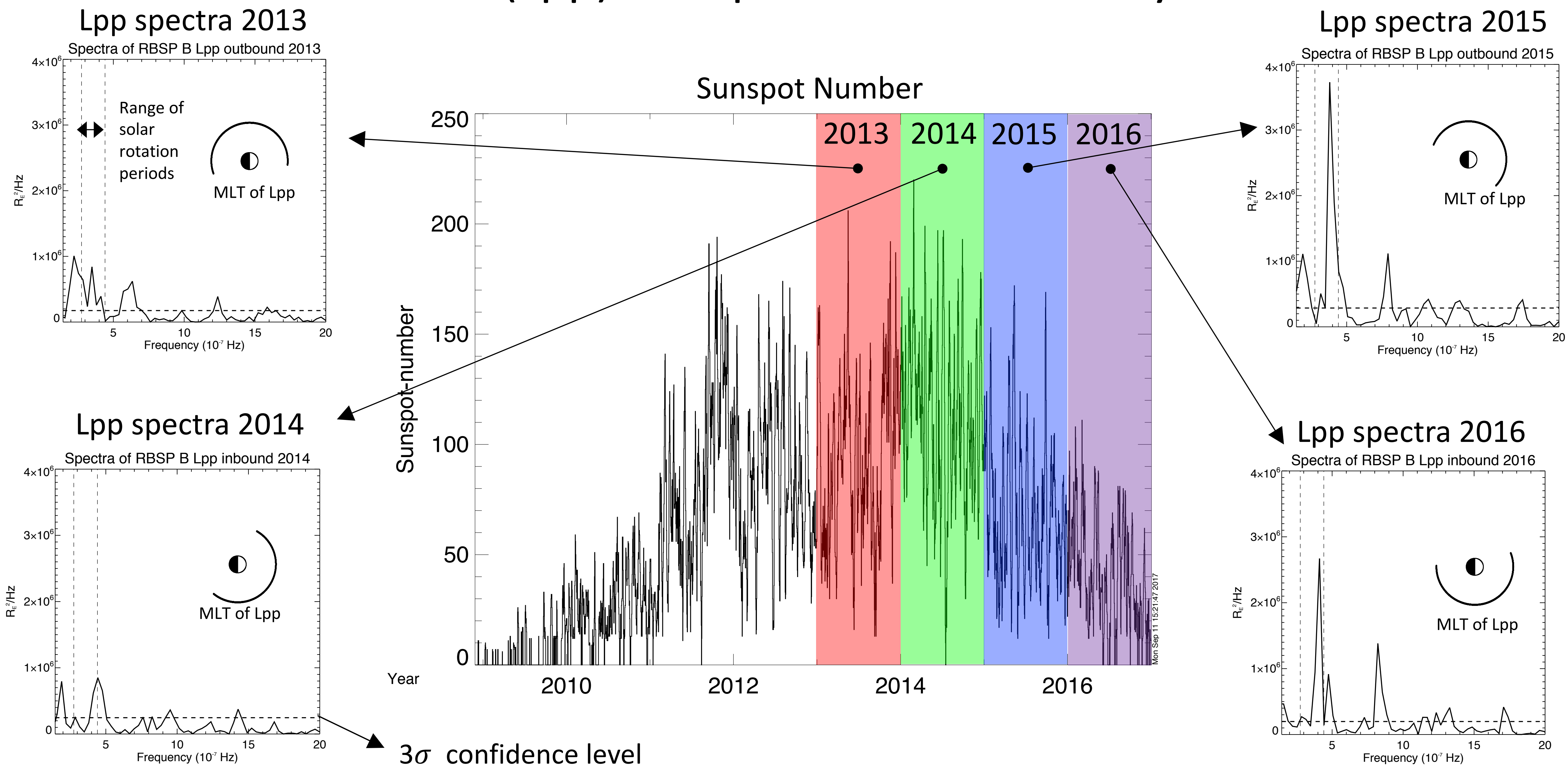
Yearly FFT power spectra of the variations in plasmapause L-value (Lpp) in the context of the solar cycle

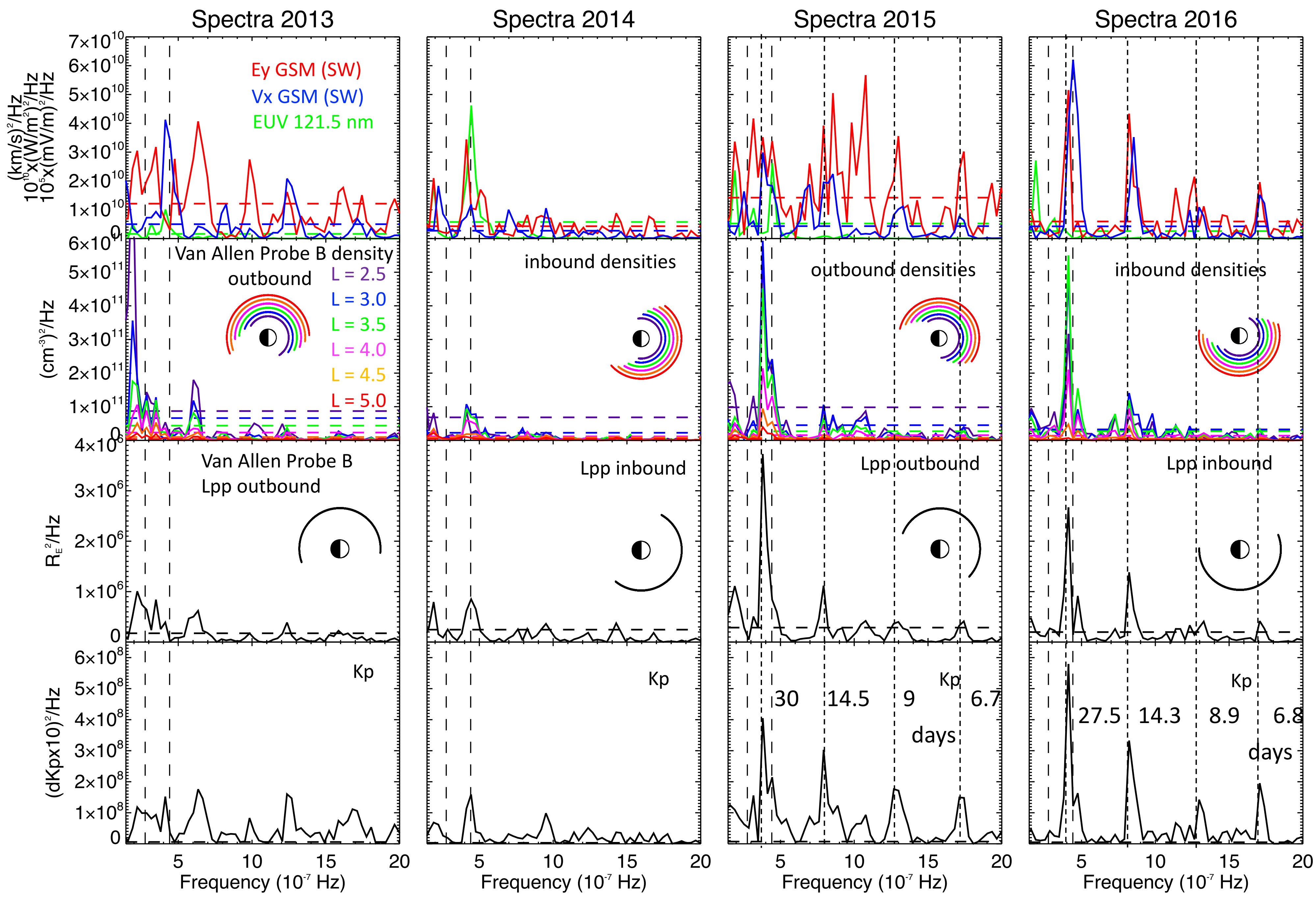


Yearly FFT power spectra of the variations in plasmapause L-value (Lpp) in the context of the solar cycle

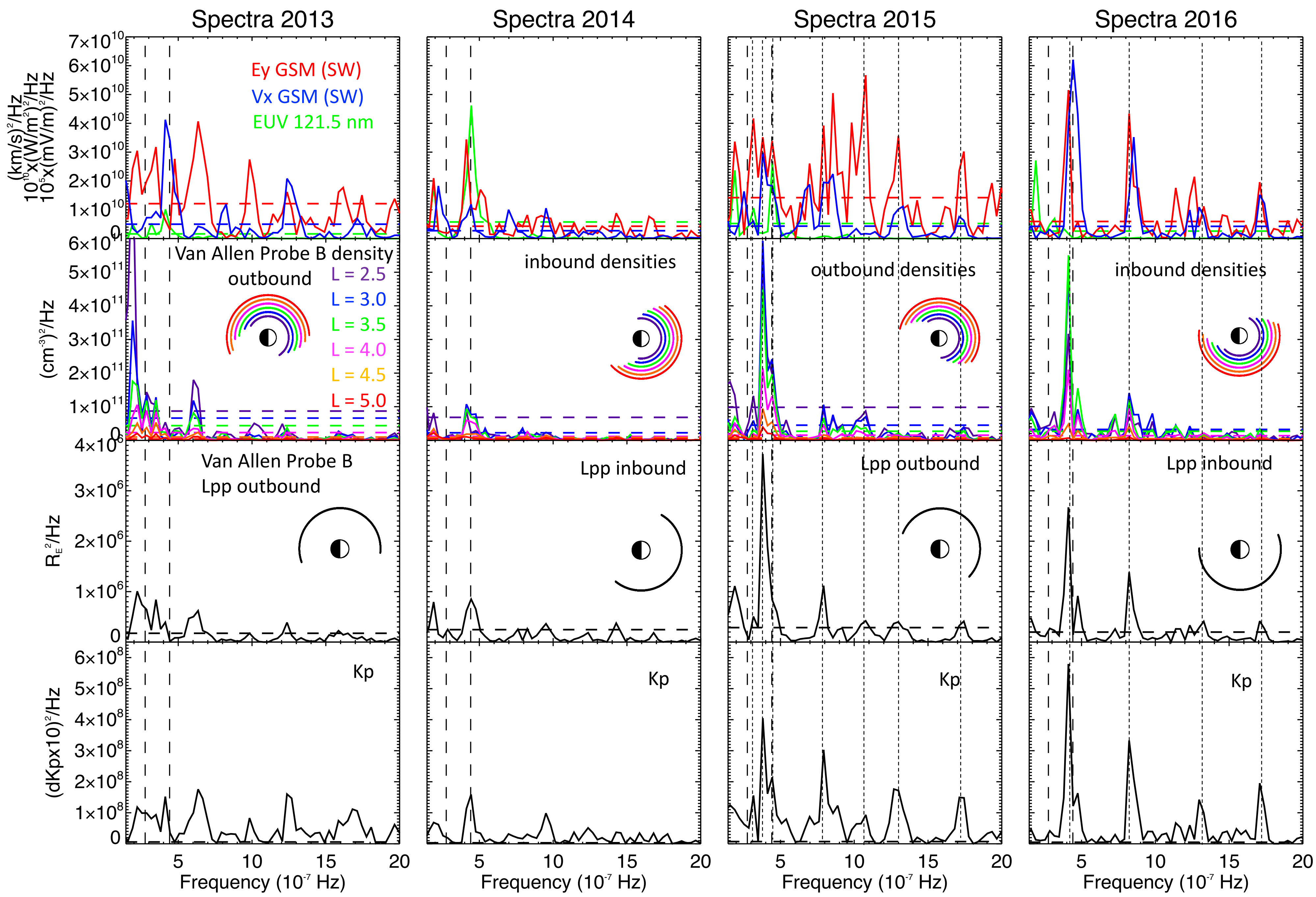


Change in the modulation of the plasmapause L-value (Lpp) with phase of the solar cycle





Spectra 2013
Spectra 2014
Spectra 2015
Spectra 2016
Ey GSM (SW)
Vx GSM (SW)
EUV 121.5 nm
(km/s)²/Hz
10¹⁰x(W/m²)²/Hz
10⁵x(mV/m)²/Hz
Van Allen Probe B density
outbound
L = 2.5
L = 3.0
L = 3.5
L = 4.0
L = 4.5
L = 5.0
inbound densities
outbound densities
inbound densities
(cm⁻³)²/Hz
Van Allen Probe B
Lpp outbound
Lpp inbound
Lpp outbound
Lpp inbound
R_E²/Hz
Kp
30
14.5
9
6.7
days
27.5
14.3
8.9
6.8
days
(dKpx10)²/Hz
Frequency (10⁻⁷ Hz)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Van Allen Probe B
Lpp outbound
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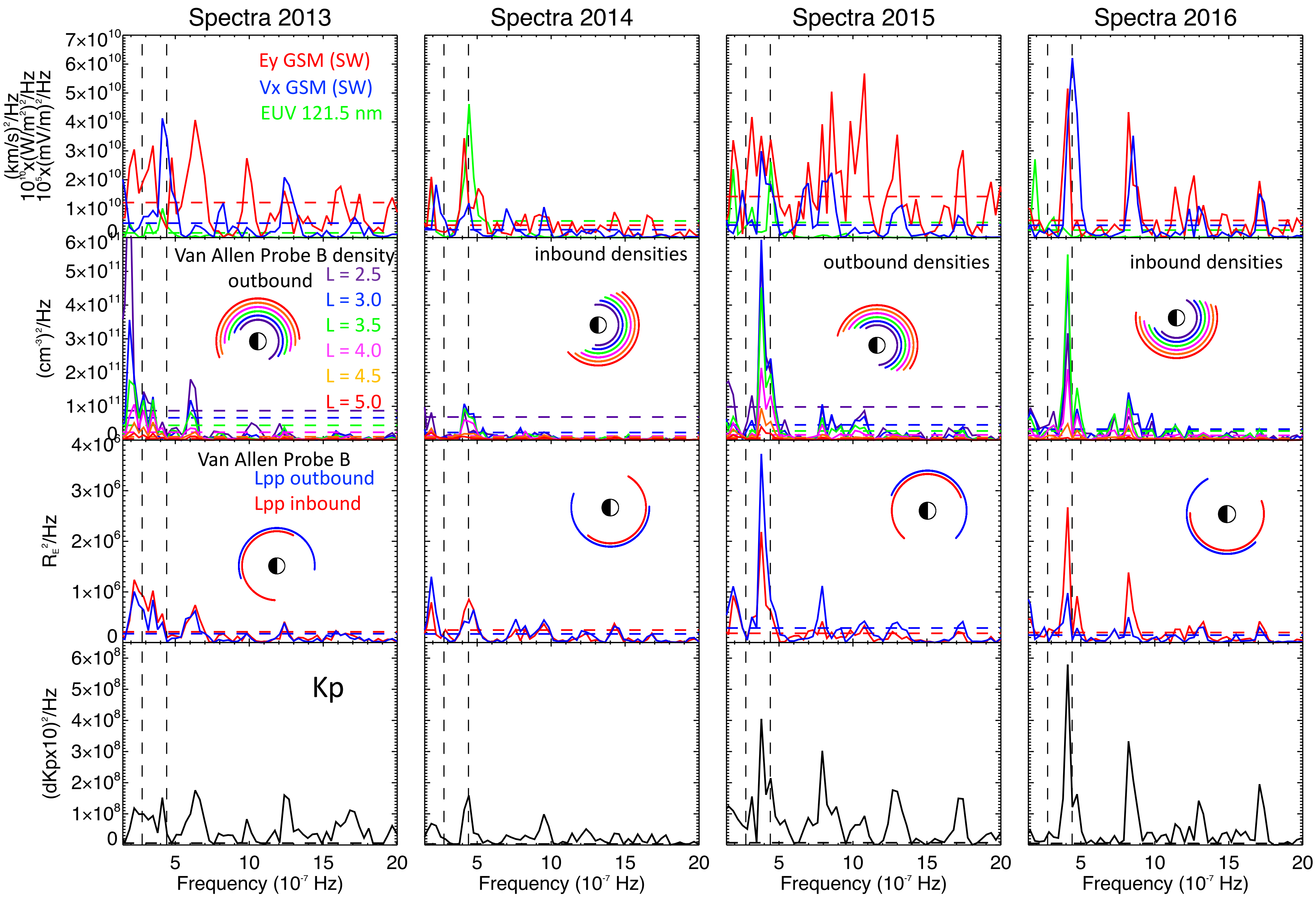
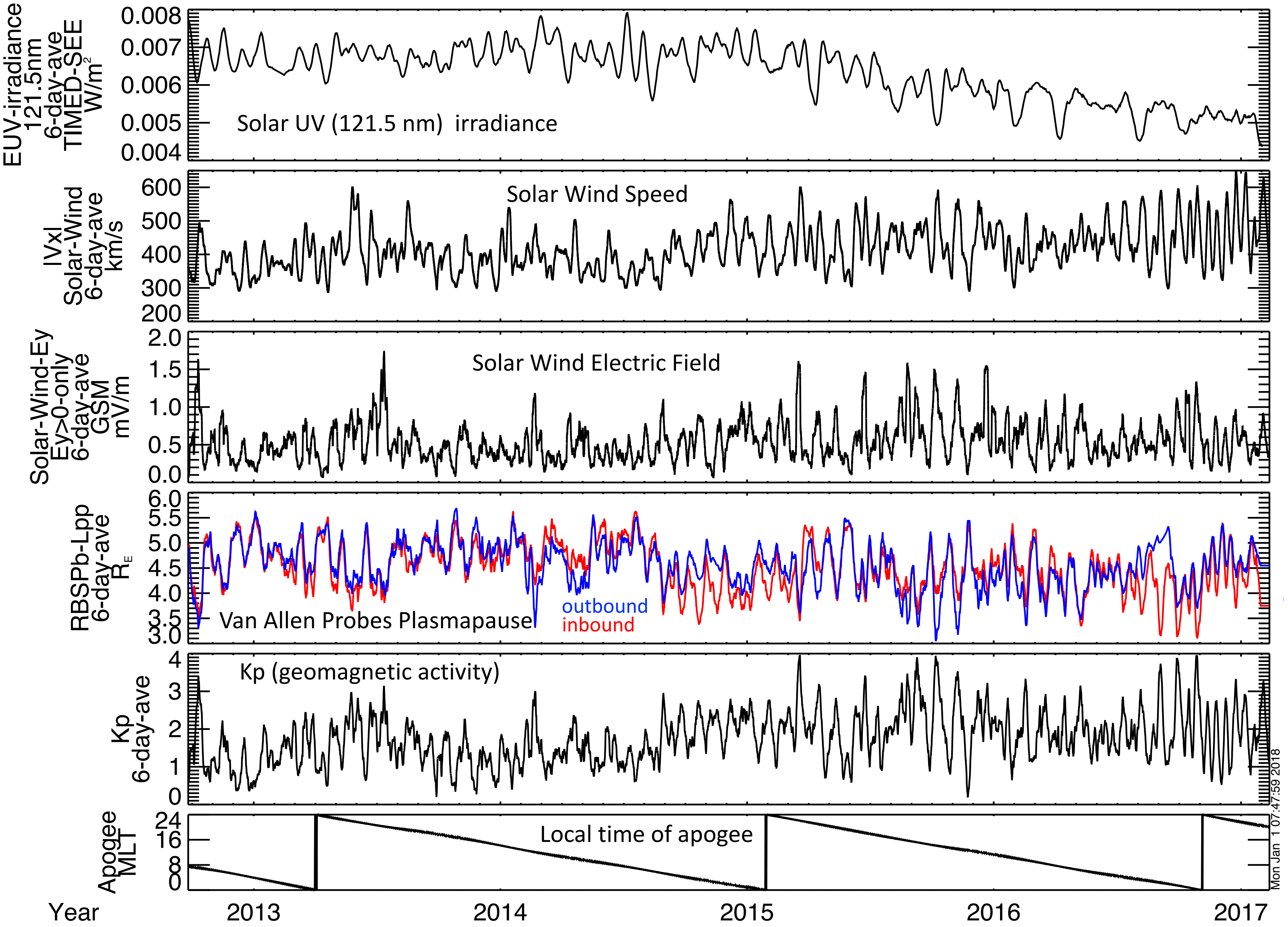
Lpp outbound
Lpp inbound
R_E²/Hz
Kp
(dKpx10)²/Hz
Frequency (10⁻⁷ Hz)



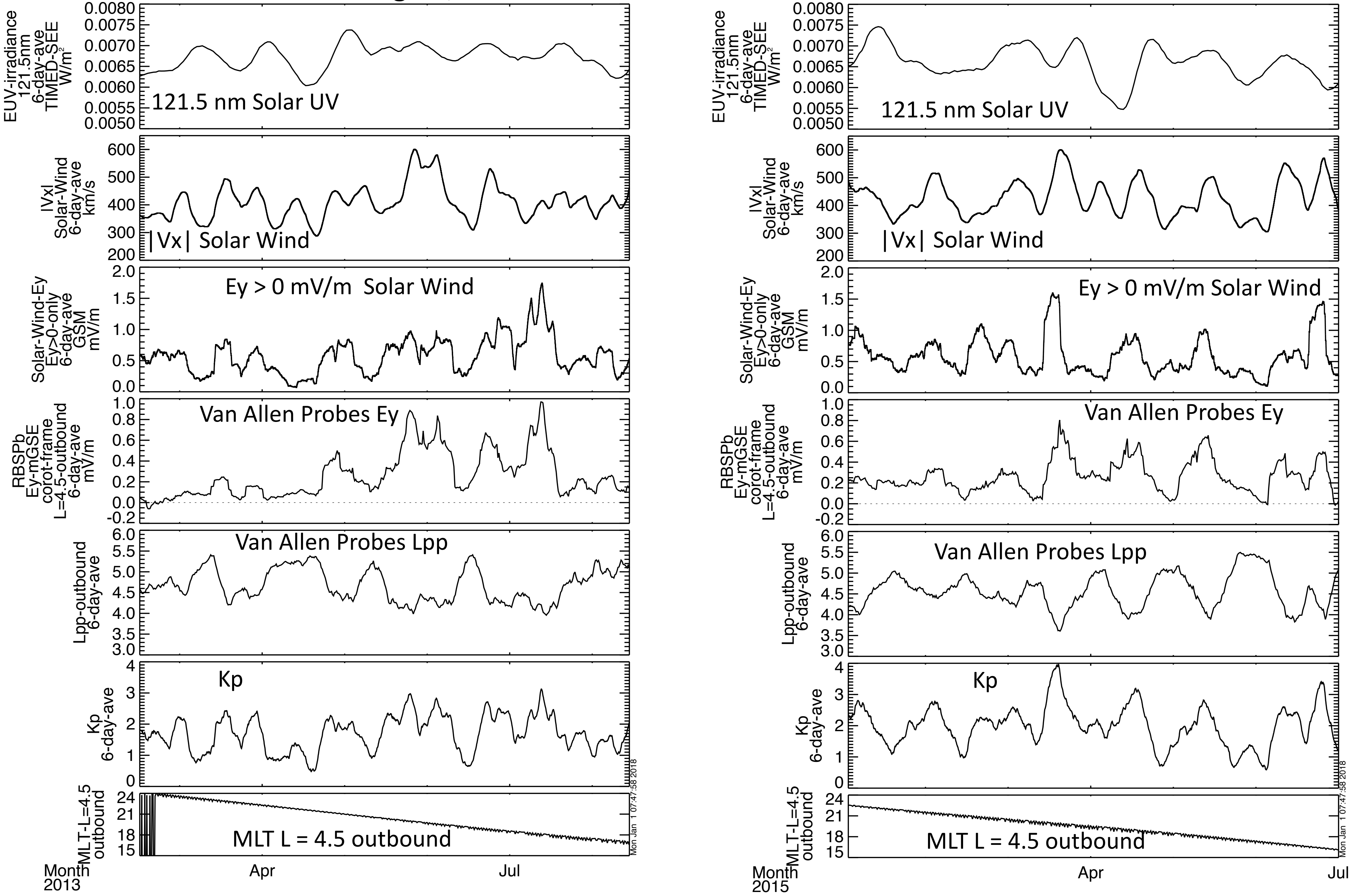
Yearly spectra of the solar EUV irradiance, solar wind speed, solar wind duskward only electric field, Van Allen Probes B cold plasma density from 2.5 to 5.0 L, inbound and outbound plasmapause L-value, and Kpx10.

As the solar cycle declines, e.g. in 2015 and 2016, Lpp, cold density and Kp clearly show increased amplitudes at frequencies of solar rotation (~27 days) and ½, 1/3, and ¼ harmonics.

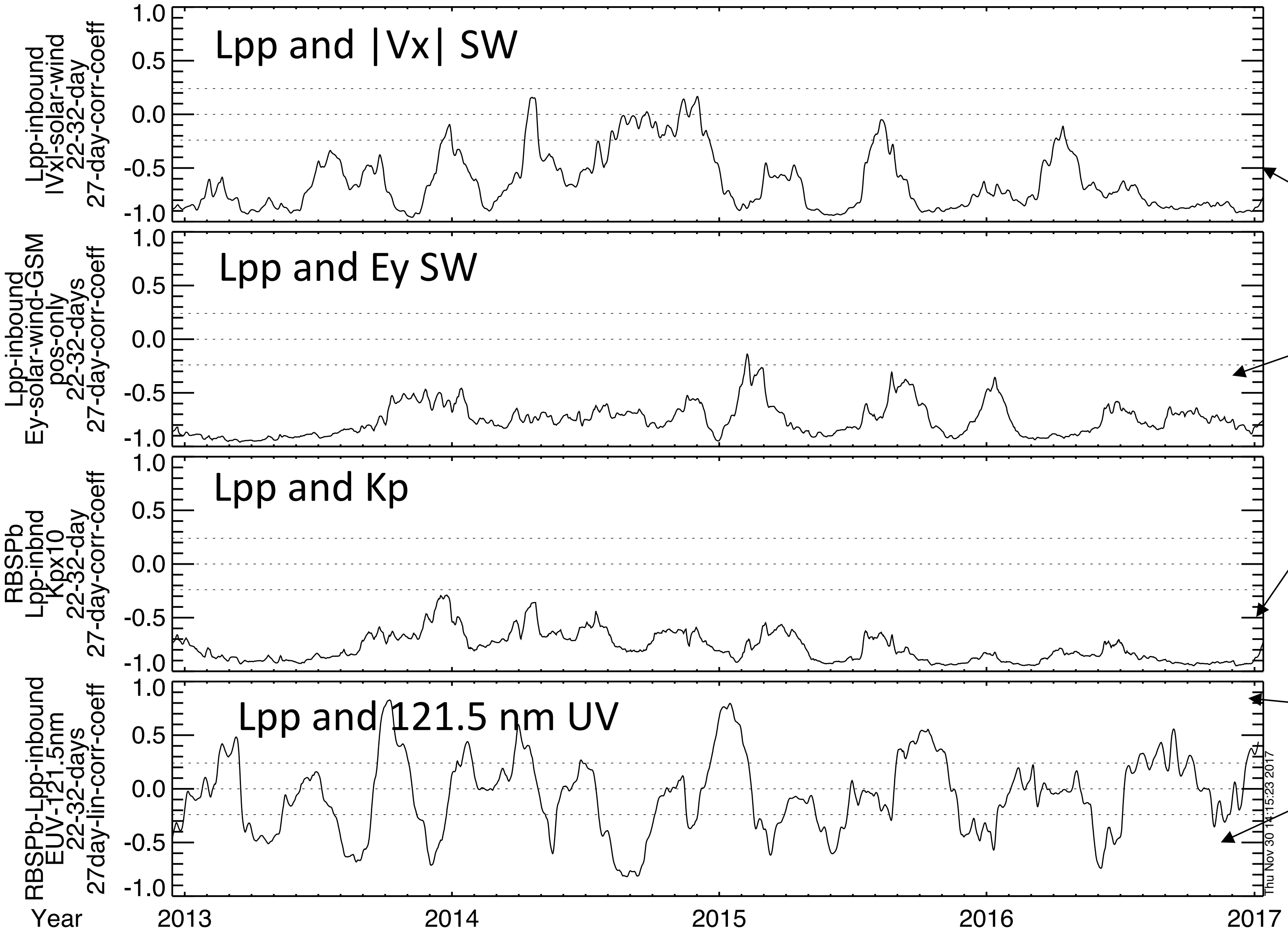


EUV-irradiance 121.5nm 6-day-ave TIMED-SEE W/m²
0.008
0.007
0.006
0.005
0.004
Solar UV (121.5 nm) irradiance
|Vx| Solar-Wind 6-day-ave km/s
600
500
400
300
200
Solar Wind Speed
Solar-Wind-Ey Ey>0-only 6-day-ave GSM mV/m
2.0
1.5
1.0
0.5
0.0
Solar Wind Electric Field
RBSPb-Lpp 6-day-ave R_E
6.0
5.5
5.0
4.5
4.0
3.5
3.0
Van Allen Probes Plasmapause
outbound
inbound
Kp 6-day-ave
4
3
2
1
0
Kp (geomagnetic activity)
Apogee MLT
24
16
8
0
Local time of apogee
Year
2013
2014
2015
2016
2017
Mon Jan 1 07:47:59 2018

Feb 15 – Aug 14, 2013 | Jan 2 – July 1, 2015



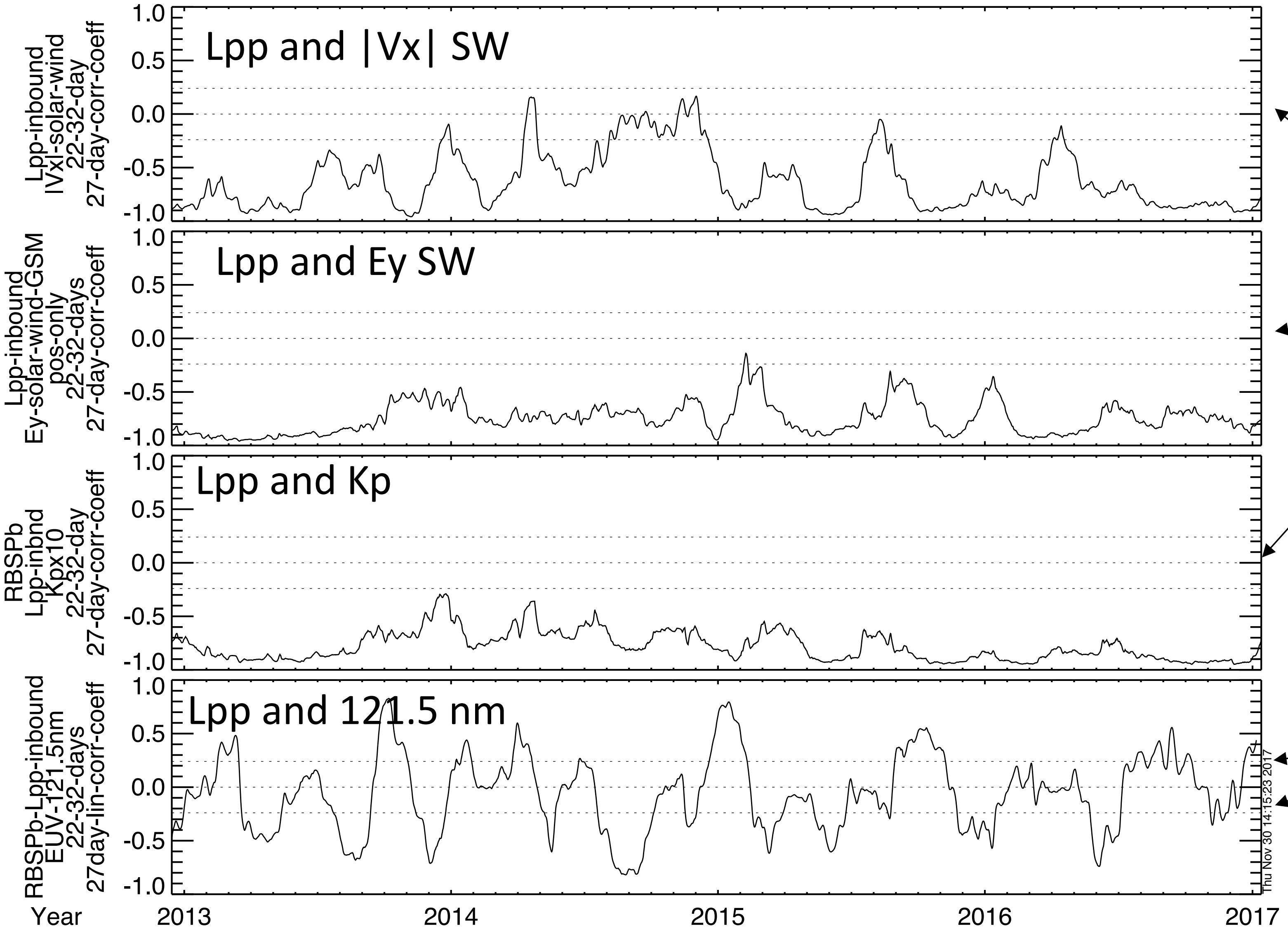
The inbound plasmapause L-value anti-correlates with the solar wind Ey (> 0 mV/m), flow speed, and Kp, and has a variable correlation and anti-correlation with EUV



Anti-Correlations (>95 % confidence, below --- line) between the inbound plasmapause L-value and Ey (> 0 mV/m) solar wind, solar wind speed (|Vx|), and Kp (all filtered 22 -32 days)

Correlation and Anti-Correlations (>95 % confidence) between plasmapause L and Lα (both filtered 22 -32 days)

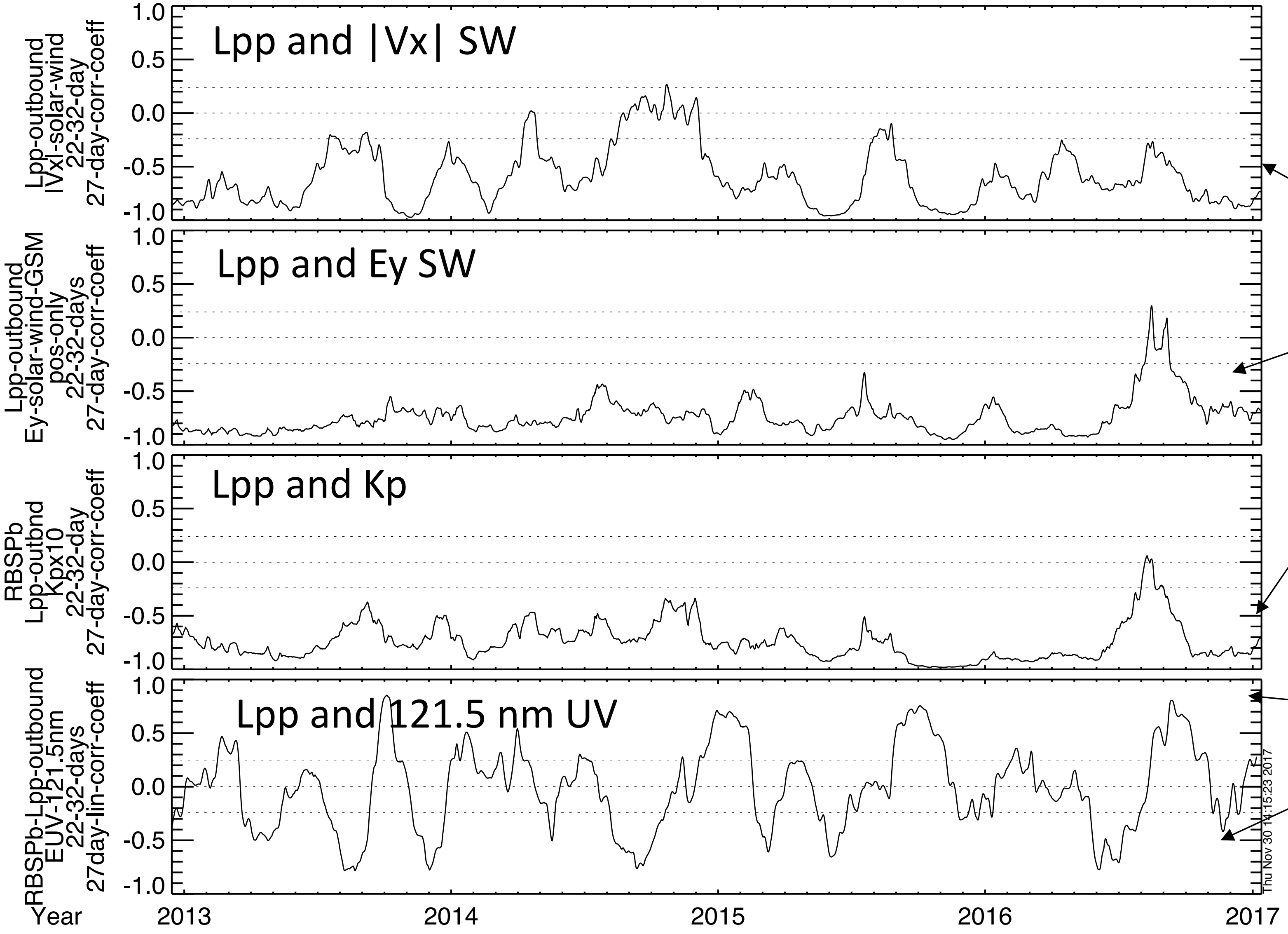
Correlation coefficients between the (22 -32 day) plasmapause location (Lpp) and solar wind speed, solar wind electric field, Kp, and UV irradiance



Anti-Correlations (>95 % confidence, below --- line) between the outbound plasmapause L-value and solar wind electric field(Ey), solar wind speed (|Vx|), and Kp (all filtered 22 -32 days)

Correlation and Anti-Correlations (>95 % confidence) between plasmapause L and Lα (both filtered 22 -32 days)

The outbound plasmapause L-value anti-correlates with the solar wind Ey (> 0 mV/m), flow speed, and Kp, and has a variable correlation and anti-correlation with EUV



Anti-Correlations (>95 % confidence, below --- line) between the outbound plasmapause L-value and Ey (> 0 mV/m) solar wind, solar wind speed (|Vx|), and Kp (all filtered 22 -32 days)

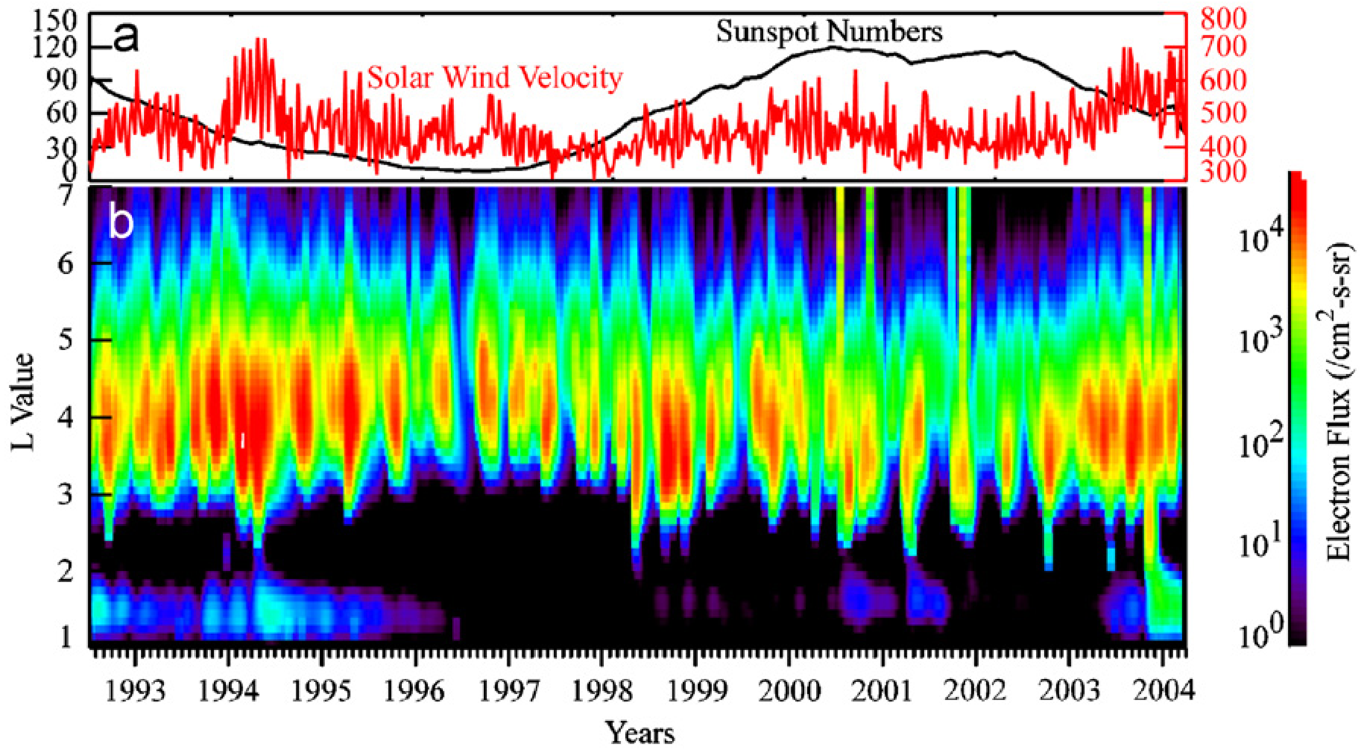
Correlation and Anti-Correlations (>95 % confidence) between plasmapause L and Lα (both filtered 22 -32 days)

Main Points

- These observations are possible because the Van Allen Probes have a near equatorial orbit over which they cover a range of geocentric distances from ~1.1 to 5.8 R_E; over the five years of the Van Allen Probes mission the apogee has made more than two complete passes through all MLT; EFW and EMFISIS instruments enabled the determination of cold plasma density over a wide range of densities.
- The structure and amplitude of the spectral peaks vary over the solar cycle.
- Most of the spectral power is located in the peaks at the solar rotation period and harmonics. This effect is most pronounced in the declining phase versus solar maximum.
- The data also allows the Van Allen Probes to assess the long term efficiency of reconnection in controlling the convection electric field in the inner magnetosphere at different locations.

Main Points

- For the first time using direct observations of the cold plasma density and dawn-dusk electric field measured by the Van Allen Probes, we have established the occurrence of modulations in plasmapause L-value and electric field strength in the inner magnetosphere being driven at solar rotation periodicities,~ 26-37 days.
- These modulations at solar rotation periodicity are significant:
  - The plasmapause L-value moves in and out by nearly ~0.7 R_E.
  - The cold plasma densities are strongly modulated from L- values 2.5 to 5 R_E, varying by up to ~35% of the average background density.
  - The dawn-dusk electric field is modulated with amplitudes ~ 0.3 mV/m, similar to the average dawn-dusk electric field value, ~0.26 mV/m
  - The Ey-mag/Ey-sw on this timescale is ~ 75%, as compared to values determined from the cross polar cap potential of ~15 to 20 % .



Adapted from Baker and Kanekal [2008]

Fig. 3. (a) A plot of the solar wind speed and sunspot number for the period 1992–2004 and (b) a plot of the $E = 2.6$ MeV electron fluxes measured by SAMPEX for the same period. The lower panel shows L-value (vertical scale) versus time (horizontal axis). The directional intensity of electrons is shown in a color-coded format according to the color bar to the right (adapted from Baker et al., 2004b).

"The long-term perspective—meaning variations on the scale of the 11-year sunspot cycle—shows that the **electron radiation belts are most enhanced in a 2–3-year interval that we call the approach to solar minimum**. **This is a period that corresponds to the time of solar coronal holes and concomitant high-speed solar wind streams.** Essentially whenever VSW exceeds 500km/s for an extended interval of time, the radiation belts become energized. We do not yet fully understand in quantitative detail how electron acceleration takes place, but considerable progress is being made. "